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3 **An evolutionary system of mineralogy, Part VIII:**
4 **The evolution of metamorphic minerals**

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12 **ABSTRACT**

13 Part VIII of the evolutionary system of mineralogy focuses on 1220 metamorphic mineral
14 species, which correspond to 755 root mineral kinds associated with varied metamorphic rock
15 types, most of which likely formed prior to the Phanerozoic Eon. A catalog of the mineral
16 modes of 2785 metamorphic rocks from around the world reveals that 94 mineral kinds often
17 occur as major phases. Of these common metamorphic minerals, 66 are silicates, 14 are oxides
18 or hydroxides, 8 are carbonates or phosphates, 4 are sulfides, and 2 are polymorphs of carbon.
19 Collectively, these 94 minerals incorporate 23 different essential chemical elements.

20 Patterns of coexistence among these 94 minerals, as revealed by network analysis and
21 Louvain community detection, point to six major communities of metamorphic phases, three of
22 which correspond to different pressure-temperature (*P-T*) regimes of metamorphosed siliceous
23 igneous and sedimentary rocks, while three represent thermally altered carbonate and calc-
24 silicate lithologies.

25 Metamorphic rocks display characteristics of an evolving chemical system, with significant
26 increases in mineral diversity and chemical complexity through billions of years of Earth history.

27 Earth's first metamorphic minerals formed in thermally altered xenoliths and contact zones
28 (hornfels and sanidinite facies) associated with early Hadean igneous activity (> 4.5 Ga). The
29 appearance of new Hadean lithologies, including clay-rich sediments, arkosic sandstones, and
30 carbonates, provided additional protoliths for thermal metamorphism prior to 4.0 Ga.
31 Orogenesis and erosion exposed extensive regional metamorphic terrains, with lithologies
32 corresponding to the Barrovian sequence of index mineral metamorphic zones appearing by
33 the Mesoarchean Era (> 2.8 Ga). More recently, rapid subduction and rebound of crustal
34 wedges, coupled with a shallowing geothermal gradient, has produced distinctive suites of
35 blueschist, eclogite, and ultrahigh pressure metamorphic suites (< 1.0 Ga). The evolution of
36 metamorphic minerals thus exemplifies changes in physical and chemical processes in Earth's
37 crust and upper mantle.

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41 **Keywords:** metamorphism; Barrovian sequence; philosophy of mineralogy; classification;
42 mineral evolution; Hadean Eon; Archean Eon; network analysis; community structure
43 analysis

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INTRODUCTION

46 *Metamorphism*: the word, itself, means change through time—"evolution" by that
47 contentious word's most basic definition. Every metamorphic mineral assemblage derives from
48 prior minerals. Each metamorphic rock has a history revealed in the varied attributes of its
49 phases—deep-time stories of changing crustal and mantle environments that epitomize mineral
50 evolution.

51 And yet, paradoxically, metamorphic minerals are among the most difficult to place into an
52 unambiguous, historical narrative. Each new suite of metamorphic phases—generation after
53 generation of prograde followed by retrograde transformations—may partially mask what
54 came before. Unlike the holocrystalline igneous assemblages featured in Part VII of this series
55 (Hazen et al. 2023), coexisting metamorphic minerals are often in disequilibrium. In this
56 contribution, though not fully resolving those ambiguities, we attempt to add metamorphic
57 minerals to the larger context of the evolving mineral kingdom.

58 The evolutionary system of mineralogy is an effort to place all of the more than 6000 mineral
59 species approved by the International Mineralogical Association's Commission on New
60 Minerals, Nomenclature, and Classification (IMA-CNMNC; <https://rruff.info/ima>, accessed 17
61 December 2023) into their historical and paragenetic contexts (Hazen 2019; Cleland et al. 2021;
62 Hazen and Morrison 2022; Hazen et al. 2022). The initial five parts of the system cataloged
63 almost 300 mineral kinds that occur as primary and secondary phases in meteorites (Hazen and
64 Morrison 2020, 2021; Morrison and Hazen 2020, 2021; Hazen et al. 2021). Part VI focused on
65 Earth's earliest mineralogy, including 262 species formed via a variety of igneous,
66 hydrothermal, aqueous alteration, and other near-surface processes (Morrison et al. 2023).

67 Part VII on “The evolution of the igneous minerals” documented 1665 primary species that
68 crystallized from a melt, with special attention to associations and antipathies among the most
69 common 115 kinds of igneous minerals (Hazen et al. 2023).

70 Our exploration of the evolution of metamorphic minerals is organized into five main
71 sections.

- 72 1. The first section considers the unusual character of metamorphic mineral evolution
73 as a historical pursuit, while outlining four significant challenges to this effort.
- 74 2. Section 2 reviews the sources of mineralogical data employed in this study, while
75 introducing eight major groups of metamorphic minerals that represent different
76 formational environments and/or compositional ranges.
- 77 3. As in prior parts of the evolutionary system, extensive tabulations of metamorphic
78 mineral co-existence data are particularly amenable to mineral network analysis
79 (Newman 2010; Morrison et al. 2017) and community structure analysis (Girvan and
80 Newman 2002; Fortunato 2010). Therefore, the third section applies these methods
81 to explore patterns of mineral coexistence in metamorphic rocks. We present a data
82 resource that records patterns of coexistence among 73 relatively common
83 metamorphic minerals in 2785 diverse metamorphic rocks, with a consideration of
84 potential preservational and anthropogenic biases in the literature of metamorphic
85 petrology.
- 86 4. Section 4, addressing the evolution of metamorphic minerals at a planetary scale,
87 considers if there have been significant changes in the nature of metamorphism
88 through more than 4 billion years of Earth history.

89 5. Finally, Appendix I details the nature and distribution of 94 of the most common
90 minerals in metamorphic rocks, as well as the modified nomenclature employed in
91 this contribution for some mineral kinds.

92

93 1. ON THE NATURE OF “METAMORPHIC MINERAL EVOLUTION”

94 In Part VIII of the evolutionary system we consider metamorphic minerals, many of which
95 first appeared prior to 2.5 Ga, though some high-pressure metamorphic lithologies appear to
96 be confined to the past billion years (Carswell and Compagnoni 2003; Palin and White 2016;
97 Brown and Johnson 2019). The strategy, as outlined in previous contributions, is to identify
98 historical processes that produced minerals with diagnostic combinations of physical and
99 chemical attributes—what we suggest are “historical natural kinds” (Boyd 1991, 1999; Hawley
100 and Bird 2011; Magnus 2012; Khalidi 2013; Ereshevsky 2014; Godman 2019; Cleland et al. 2021;
101 Hazen et al. 2022). By so doing, the evolutionary system complements standard taxonomic
102 protocols of the IMA-CNMNC, which differentiate each mineral “species” based on its unique
103 combination of major element chemistry and idealized atomic structure (e.g., Burke 2006; Mills
104 et al. 2009; Schertl et al. 2018; Hatert et al. 2021; Hazen 2021; Hawthorne et al. 2021).

105 Here we consider the diversity, distribution, and ages of 1220 metamorphic minerals, all but
106 five of which (*Fe-dolomite*, *olivine*, *phengite*, *plagioclase*, and *silicate glass*) are species
107 approved by the IMA-CNMNC (<https://rruff.info/ima/>; accessed 17 March 2023). We define a
108 metamorphic mineral as a naturally occurring solid phase that forms by the transformation of
109 one or more prior solid phases through the sustained action of temperature and/or pressure.
110 This definition is consistent with that of Philpotts and Ague (2009): “Metamorphism is the sum

111 of all changes that take place in a rock as a result of changes in the rock's environment; that is,
112 changes in temperature, pressure (directed as well as lithostatic), and composition of fluids.
113 The changes in a rock may be textural, mineralogical, chemical, or isotopic." Note, however,
114 that we restrict the focus to mineralogical changes resulting from $T > \sim 150$ °C up to
115 temperatures that cause melting and magma genesis. By this definition, we include regional
116 metamorphism from zeolite to ultrahigh temperature (UHT) facies; contact (i.e., thermal)
117 metamorphism from hornfels and sanidinite facies; and ultrahigh pressure metamorphism from
118 blueschist, eclogite, and ultrahigh pressure (UHP facies). However, we do not consider
119 alteration by impacts, lightning, or other transient processes that are considered in other parts
120 of this series (e.g., Hazen et al. 2023; Morrison et al. 2023). Furthermore, alterations that result
121 from biological sources, notably pyrometamorphism by hydrocarbon combustion, as well as
122 metamorphism of biomediated protoliths such as coal and phosphorites, will be considered in a
123 subsequent part of this series.

124 Metamorphism might seem the quintessential example of mineral evolution because
125 metamorphic assemblages by definition require sequential mineralogical changes through time.
126 However, the conventions of the evolutionary system of mineralogy result in four inherent
127 difficulties related to: (1) determining the timing of metamorphism; (2) documenting the
128 sequence and environment of metamorphic mineral paragenesis; (3) dealing with the critical
129 importance of many mineral's variable compositions owing to solid solution; and (4)
130 deciphering the important roles of fluids in metamorphism. In this contribution we only
131 partially resolve these four challenges.

132

133 1. *The timing of metamorphic mineralization*: Mineral evolution, as originally presented by
134 Hazen et al. (2008), considers the near-surface (< 3 km) mineralogy of terrestrial planets
135 and moons. Three factors were cited to justify this depth criterion: (1) these are the
136 minerals most easily documented on Earth, (2) they are the minerals we are most likely to
137 observe on other terrestrial worlds, and (3) interactions with cellular life occur primarily
138 in this near-surface domain. Any consideration of the mineral evolution of much deeper
139 regimes must inevitably lead to increased degrees of speculation and uncertainty.

140 Complications may arise because Earth's near-surface mineral inventory originates
141 both from near-surface paragenesis (e.g., volcanism, evaporation, biomineralization), and
142 from much deeper processes (igneous intrusion, deep hydrothermal mineralization,
143 regional and ultrahigh pressure metamorphism). In the latter instances, a mineral is
144 included in our tabulations only if it subsequently appears in the shallow crust, usually
145 through some combination of volcanic, tectonic, and/or erosional processes.
146 Consequently, the timing of a metamorphic mineral's appearance in a relatively shallow
147 crustal environment likely postdates its formation age by tens to as much as hundreds of
148 millions of years (e.g., Ganade et al. 2023)—a vast interval during which retrograde
149 compositional and structural alterations are common.

150 Evidence for this protracted history is provided by the observation that the volume of
151 metasedimentary rocks at Earth's surface for different geological ages has significantly
152 decreased over the past 600 Myr. An average of > 40 vol % of the exposed lithologies of
153 Neoproterozoic age (1000 to 541 Ma) are metamorphic rocks, compared to < 20 vol % of
154 surface lithologies from the subsequent Phanerozoic Eon (Bluth and Kump 1991; Peters

155 and Husson 2017; Peters et al. 2018; Lipp et al. 2021; <https://macrostrat.org>, accessed 31
156 December 2022). In spite of this disparity, we suggest that the total volume of
157 metasediments, including those still buried deep within the crust, has likely not
158 diminished significantly over the past billion years. The occurrences, extents, and ages of
159 near-surface metamorphic minerals are as much functions of the rates of tectonic and
160 erosional processes as they are of the deep transformation of protoliths at pressure and
161 temperature. Therefore, somewhat paradoxically, the evolution of metamorphic minerals
162 at once provides some of the clearest examples of an evolutionary sequence of
163 mineralogical states, while defying any simple statistical evaluation of the changing
164 diversity and distribution of metamorphic minerals through deep time.

165

166 2. *The sequence of metamorphic mineralization:* The inevitable extended time intervals
167 required for a protolith's burial, metamorphism, and uplift are particularly challenging in
168 any attempt to document the exact sequence of a metamorphic mineral's evolution. On
169 the one hand, metamorphic minerals, in contrast to those from most other paragenetic
170 processes, represent a true *sequential* and *congruent* evolutionary pathway. Every
171 metamorphic mineral assemblage was derived by the stepwise alteration of an igneous,
172 sedimentary, or metamorphic protolith (Goldschmidt 2011), often with multiple
173 transformations that reflect changes in the mineralizing temperature, pressure, and/or
174 fluid composition (Barrow 1893; Eskola 1920; Bowen 1940; Tilley 1951). One can thus
175 visualize an evolutionary metamorphic pathway with successive prograde and retrograde
176 chemical reactions, illustrated for example on pressure-temperature-time diagrams

177 (Philpott and Ague 2009, their Figure 16-6, and references therein) or through a series of
178 tree or network graphs (e.g., Heaney 2016; Morrison et al. 2017).

179 On the other hand, the temporal details of a metamorphic rock's history may be
180 scrambled and difficult to interpret. Many metamorphic processes occur deep in the crust
181 or upper mantle; hundreds of millions of years may be required for tectonic processes
182 and erosion to expose highly altered metamorphic terrains.

183 An additional conundrum relates to metamorphic rocks, particularly lower grade
184 contact and regional metamorphic formations, with biologically-derived protoliths. The
185 processes of contact and regional metamorphism likely commenced long before the first
186 living cells, and many metamorphic formations are unambiguously abiotic—i.e., arising
187 via purely chemical and physical processes. However, the burial and alteration of coal,
188 phosphorites, and a wide range of fossil-bearing limestone, marl, shales, and other
189 biogenic deposits must postdate their Phanerozoic origins. Furthermore, the resultant
190 metamorphic minerals, even if representing the same IMA-CNMNC-approved species as
191 those in much more ancient abiotic rocks, may preserve diagnostic biosignatures in their
192 trace elements, isotopes, morphologies, and other attributes. If so, then by the
193 conventions of the evolutionary system these metamorphic phases represent distinct and
194 relatively recent biologically mediated mineral kinds. Consequently, we defer discussion
195 of the metamorphism of biotic protoliths until the final part of this series.

196

197 3. *Mineral solid solution*: Most diagnostic metamorphic minerals display significant solid
198 solution, ranging from binary systems [e.g., olivine (Mg,Fe)₂SiO₄], to minerals with 4 or

199 more chemical degrees of freedom [e.g., “hornblende”
200 $(\text{Na,K})\text{Ca}_2(\text{Mg,Fe}^{2+},\text{Al,Fe}^{3+})_5(\text{Si,Al})_8\text{O}_{22}(\text{OH,F,Cl})_2$]. Continuous compositional variations with
201 changes in temperature, pressure, and/or fluid composition are central to understanding
202 metamorphic processes, especially teasing out the evolution from one mineral
203 assemblage to the next. However, the nomenclature adopted by the IMA-CNMNC, as well
204 as in the evolutionary system in its present preliminary form, are ill-suited to describing
205 such subtle yet critical shifts in element ratios.

206 For example, both the IMA and evolutionary systems employ the end-member olivine
207 minerals forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4), neither of which is particularly useful
208 when dealing with the variable intermediate Mg-Fe compositions of olivine in
209 metamorphosed mafic and ultramafic rocks. Consequently, we add *olivine* as a mineral
210 kind defined as $(\text{Mg,Fe})_2\text{SiO}_4$ with $0.3 < \text{Fe}/(\text{Fe} + \text{Mg}) < 0.7$. Similarly, while the IMA
211 system names only end-member compositions in the ternary of Ca-Na-K feldspars as valid
212 mineral species, most natural specimens have intermediate compositions along either the
213 Ca-Na (plagioclase) or Na-K (alkali feldspar) binaries and, in the extreme case of ultrahigh
214 temperature facies, feldspar compositions may lie well within the ternary region (e.g.,
215 Harley 2021, their Figure 20).

216 This situation is especially concerning when comparing the mineralogy of very
217 different protoliths. For example, near end-member forsterite formed during the contact
218 metamorphism of dolomite differs significantly from intermediate olivine in metabasalt
219 with $\text{Mg} > \text{Fe}$. Both minerals are classified as “forsterite” in the IMA formalism, though we
220 call intermediate Mg-Fe olivine compositions *olivine*. Until we have much more

221 information on the compositional idiosyncrasies associated with minerals from different
222 metamorphic environments (i.e., the “metamorphic mineral kinds”), these ambiguities in
223 nomenclature will limit our efforts.

224 An additional challenge with respect to mineral nomenclature is the use of some
225 names in the metamorphic petrology literature that do not coincide with approved
226 mineral species. For example, “breunnerite” is not an approved mineral name, yet it is
227 commonly applied to intermediate compositions of the magnesite—siderite [(Mg,Fe)CO₃]
228 solid solution, where $0.1 > \text{Fe}/(\text{Mg}+\text{Fe}) > 0.3$. In our study, all such occurrences are
229 reported as the Mg end-member, *magnesite*. Ankerite, by contrast, is an IMA-approved
230 name for minerals in which $\text{Fe} > \text{Mg}$ on the dolomite—ankerite [Ca(Mg,Fe)(CO₃)₂] binary.
231 However, “ankerite” has been traditionally employed in the metamorphic petrology
232 literature for a range of ferroan dolomites, including the majority with $\text{Fe}/(\text{Mg} + \text{Fe}) < 0.5$
233 (e.g., Chang et al. 1996; Ferry 1996; Ferry et al. 2015)—all occurrences that IMA would
234 designate as dolomite. Consequently, important information related to intermediate
235 compositions is lost through standardized mineral nomenclature.

236 Accordingly, in this study we employ several names for solid solutions. *Augite* and
237 *pigeonite* are anomalous IMA-approved names for broad solid solutions among Ca-Mg-Fe
238 clinopyroxenes. In this contribution we adopt the non-approved names “*Fe-dolomite*” for
239 *dolomite* with $0.15 < \text{Fe}/(\text{Fe} + \text{Mg}) < 0.50$, “*olivine*” for examples with $0.3 < \text{Fe}/(\text{Fe} + \text{Mg}) <$
240 0.70 , and “*plagioclase*” for intermediate Ca-Na feldspar compositions with $0.15 < \text{Ca}/(\text{Ca} +$
241 $\text{Na}) < 0.85$. We also employ a number of group names such as *biotite*, *hornblende*,
242 *scapolite*, *serpentine*, and *tourmaline* to lump several closely related species—a

243 convention that is especially useful for mineral groups for which the exact species is rarely
244 reported in the petrologic literature (see Appendix 1).

245

246 4. The *role of fluids*: Another ambiguity, as yet imperfectly resolved in our treatment, relates
247 to the role of fluid alteration during metamorphic processes. Hydration/dehydration,
248 carbonation/decarbonation, and other fluid-rock interactions are integral to many
249 metamorphic reactions. However, metasomatic alteration, by which a protolith reacts
250 with external fluids, introduces complexities. We define metamorphism as mineralogical
251 changes induced by changes in temperature and/or pressure, whether or not a fluid of
252 differing composition is also involved. By contrast, in metasomatism mineralogical
253 changes are caused by an influx of fluids of differing composition, whether or not changes
254 in temperature and/or pressure are involved.

255 The processes of metamorphism and metasomatism thus differ conceptually;
256 however, sharp boundaries do not exist between the two (Ramberg 1952). For example,
257 Joplin (1968) notes that their “division of contact metamorphism and contact
258 metasomatism into separate chapters is an artificial one since the two processes are very
259 closely associated and cannot readily be separated.” Consequently, in some cases
260 outlined below we attempt to include minerals that have likely been compositionally
261 transformed by proximal fluids (e.g., boron-fluorine metasomatism in some skarns; Tilley
262 1951; Marincea and Dumitras 2019), whereas in other instances we exclude minerals for
263 which the alteration to a new phase appears to be principally related to fluids derived
264 from sources more distant in space and/or time. Note that weathering, lithification, and

265 diagenesis, as well as seafloor alteration by serpentinization, will be considered in Part IX,
266 even if temperatures may be significantly greater than 150 °C in some instances.

267

268 In spite of these four challenges, we adopt the strategy employed in Part VII (igneous
269 mineral evolution; Hazen et al. 2023) by tabulating the modes of diverse metamorphic rocks
270 and investigating observed patterns of mineral coexistence, both their associations and their
271 antipathies.

272

273

2. ON THE DISTRIBUTION OF MINERALS IN METAMORPHIC ROCKS

274 An examination of the varied formation processes of all mineral species approved by the
275 IMA-CNMNC (Hazen and Morrison 2022; <https://rruff.info/ima>, accessed 17 January 2022)
276 reveals 1220 minerals that have been reported as phases in metamorphic rocks. Accordingly,
277 we tabulate 1215 metamorphic mineral species approved by the IMA-CNMNC, as well as *Fe-*
278 *dolomite*, *olivine*, *phengite*, *plagioclase*, and *silicate glass* [see **Supplementary Table 1** and
279 associated **Supplementary Read-Me File 1**; see also Hazen and Morrison (2022; their
280 **Supplementary Table 1** and additions)]. **Table 1** catalogs 5 **Supplementary Tables** and an
281 interactive graphical figure associated with this contribution.

282

283 **Table 1.** Catalog of 5 Supplementary Tables (see also 5 associated Supplementary Read-Me
284 Files) and an Interactive Graphical Figure (see figure caption for links and instructions).

285
286 Supplementary Table 1. A list of 1220 metamorphic mineral species (including *Fe-dolomite*,
287 *plagioclase*, and *silicate glass*), and their correspondence to 755 root mineral kinds, with
288 compositions and distributions among 8 metamorphic rock types.

289 Supplementary Table 2. A list matching 652 IMA-approved species with their associated 187
290 mineral kinds, which are defined by lumping two or more species.

291 Supplementary Table 3. A matrix listing the modes of 2785 metamorphic rocks. We record the
292 distribution of 94 of the most common metamorphic minerals among these rocks.

293 Supplementary Table 4. A 73 x 73 symmetrical matrix that records the numbers of co-
294 occurrences among 73 of the minerals in Supplementary Table 3. We do not include 21
295 minerals that occur commonly in multiple types of metamorphic environments.

296 Supplementary Table 5. A 73 x 73 symmetrical matrix (derived from Supplementary Table 4)
297 that records the percentage of the less common mineral that co-occurs with the more
298 common mineral.

299 Interactive Figure 1. A unipartite network of coexistence among 73 of the most common
300 metamorphic minerals, based on data in Supplementary Tables 3, 4, and 5. The nodes are
301 colored according to 6 communities, based on Louvain Community Detection.

302
303

304 *Mineral natural kinds*: The list of 1220 metamorphic mineral species is significantly modified in
305 the evolutionary system of mineralogy by rules for “lumping and splitting” (Hazen et al. 2022).
306 We have thus consolidated the list of 1220 minerals to recognize 755 “natural kinds” (Hawley
307 and Bird 2011; Magnus 2012; Bird and Tobin 2015; Hazen 2019; Cleland et al. 2021) of
308 metamorphic minerals [Appendix I; **Supplementary Table 2 and associated Supplementary**
309 **Read-Me File 2**; see also Hazen et al. 2022, their Supplementary Table 1 and additions)].

310 Of the 1220 metamorphic mineral species, 568 correspond exactly to 568 root mineral kinds,
311 whereas the other 652 species are lumped into 187 root mineral kinds. The majority of the
312 resulting 755 metamorphic root mineral kind names (each *italicized*) are the same as the
313 corresponding IMA mineral species name; thus, the IMA species albite is equivalent to the root
314 mineral kind *albite*. In 26 instances, we adopt the IMA-approved mineral name, minus its suffix
315 or prefix, as the root mineral name for groups of two or more closely-related species; thus,
316 *chabazite* is the root mineral name for the four lumped species chabazite-Ca, chabazite-K,
317 chabazite-Mg, and chabazite-Na, whereas *apatite* is the root mineral name for fluorapatite and
318 hydroxylapatite. In 18 instances (*androsite, apophyllite, biotite, chlorite, ellestadite, hogbomite,*
319 *hornblende, kspar, leakeite, melilite, orthoenstatite, Os-Ru alloy, Pd-Pt-Rh alloy, scapolite,*
320 *serpentine, taaffeite, tourmaline, and wolframite*), we employ an unapproved mineral kind
321 name for a group of closely-related IMA-approved mineral species. Thus, for example,
322 *tourmaline* is the root mineral kind name for 18 IMA-approved species formed by metamorphic
323 processes in the tourmaline group.

324 As suggested above, this proposed nomenclature is a first step in developing a much richer
325 mineral taxonomy related to historical mineral kinds. In the case of metamorphic minerals,

326 numerous additional subdivisions are suggested. For example, our approach has yet to
327 recognize and name many of the intermediate compositions of such important metamorphic
328 mineral groups as amphiboles, carbonates, feldspars, micas, olivines, or pyroxenes. Until large
329 databases of mineral compositions and their petrologic contexts are interrogated with cluster
330 analysis (e.g., Gregory et al. 2019; Boujibar et al. 2021; Hystad et al. 2021), any consideration of
331 mineral associations will be limited.

332

333 *Metamorphic paragenetic modes*: One approach to understanding metamorphic mineral
334 evolution lies in documenting the coexistence of phases in different groups of metamorphic
335 rocks. Supplementary Table 1 lists the distribution of these phases among 8 distinctive groups
336 of metamorphic rocks (see also [Table 2](#)), each with characteristic mineral assemblages and each
337 designated by a 3-letter abbreviation, as well as the paragenetic mode number (*p##*) originally
338 employed by Hazen and Morrison (2022). In the course of this work we have expanded and
339 revised the list of paragenetic modes associated with metamorphic minerals. In Supplementary
340 Table 1, as indicated in red highlights, we have added 273 new combinations of a mineral
341 species and metamorphic paragenetic mode, while removing 7 entries for which no supporting
342 information could be found.

343

344

345 **Table 2.** Division of mineral species and “root mineral kinds” among eight metamorphic paragenetic modes
346 as recorded in Supplementary Table 1, with estimated ages of occurrence.

347	Paragenetic Mode	Code^a	Age (Ga)	# Species^b	#Unique^c	# Kinds^d
348	Pyrometamorphism of xenoliths	XEN; p09	> 4.5	173	87	130
349	Contact metamorphism	CON; p31	> 4.0	424	241	264
350	Metamorphic Ba/Mn/Pb/Zn deposits	BAM; p32	> 3.0	449	375	310
351	Ophiolites	OPH; p38	> 3.0	109	69	96
352	High-pressure metamorphism	HPM; p39	< 1.0	113	29	89
353	Regional metamorphism	REG; p40	< 3.0	351	151	205
354	Mantle metasomatism	MET; p41	> 4.0	37	5	35
355	Shear-induced minerals	SHE; p43	> 4.0	30	2	29

356 ^a Paragenetic codes from Hazen and Morrison (2022).

357 ^b Number of IMA-CNMNC-approved species associated with this paragenetic mode.

358 ^c Number of IMA-CNMNC-approved species unique to this paragenetic mode.

359 ^d Number of root mineral kinds associated with this paragenetic mode.

360

361 In the following sections, we summarize the compositions, processes, diversity, and possible
362 ages of the eight groups of metamorphic minerals considered in this contribution.

363

364 1. Pyrometamorphism of xenoliths (XEN; p09): Thermally altered xenoliths are derived from
365 both crustal and mantle sources subjected to high-temperature, low-pressure hornfels
366 and sanidinite facies metamorphism by igneous melts (Grapes 2006). Typically formed at
367 temperatures above 900 °C and pressures less than 0.5 GPa, pyrometamorphic suites
368 were likely the earliest of Earth’s near-surface metamorphic lithologies. The first
369 protoliths were mafic and ultramafic igneous rocks from the earliest Hadean Eon (> 4.5
370 Ga), though xenoliths from virtually all of Earth’s diverse igneous, sedimentary, and
371 metamorphic lithologies have been subsequently subjected to pyrometamorphic
372 conditions.

373 We identify 173 IMA-approved mineral species, corresponding to 130 mineral kinds,
374 that formed by xenolith pyrometamorphism. Based on our surveys, 87 of these phases
375 are unique to xenoliths. Of special note are the more than 50 Ca-bearing limestone
376 xenolith minerals from the intensively studied lavas of the Somma-Vesuvius Complex,
377 Naples, Italy (<https://mindat.org>; accessed 06 January 2023).

378 Note that under this heading we do not include several groups of relatively recent (<
379 400 Ma) biologically-mediated pyrometamorphic assemblages, including minerals
380 formed in coal mine fires or by hydrocarbon fires, notably from the Hatrurim Basin
381 (Grapes 2006; <https://mindat.org>, accessed 17 March 2023). Similarly, pyrometamorphic
382 minerals from coal and other carbon-rich lithologies altered as xenoliths in lava or
383 through contact metamorphism are deferred until Part XII of this series.

384

385 2. Thermal alteration via contact metamorphism (CON; p31): Contact metamorphism
386 occurs when an igneous intrusive body thermally alters the older host country rock,
387 including sedimentary, igneous, and metamorphic lithologies. Contact metamorphism is
388 similar in many respects to the thermal alteration of xenoliths. However, contact
389 metamorphism often differs by the extent of reactions with proximal aqueous fluids,
390 notably those rich in carbonate and phosphate, as well as sulfate, borate, halogens, and
391 other solutes derived from both the magma and the country rock (Einaudi et al. 1981;
392 Einaudi and Burt 1982; Button 1982; Falkowski et al. 2000; Klein 2005; Kappler et al.
393 2005). We tabulate 424 mineral species (264 mineral kinds) that form through contact
394 metamorphism, including phases that arise through reactions with local fluids. We find

395 that 241 of these species are unique to contact metamorphic environments. Note that
396 continents with deep roots and active hydrological cycles also formed minerals by high-
397 temperature aqueous alteration through metasomatism—processes to be considered
398 further in Part IX of this series.

399 Contact metamorphism is an ancient process that must have commenced as early as a
400 second generation of magma penetrated the first cooling Hadean crust. The subsequent
401 history of contact metamorphism and its expanding mineral diversity parallels the
402 evolution of ever more differentiated crustal lithologies. Of special interest are
403 limestones and dolomites, which are particularly susceptible to transformation by hot
404 fluids emanating from acid intrusions—assemblages known as skarns (Bowen 1940;
405 Harker 1950; Tilley 1951).

406

407 3. Metamorphic Ba/Mn/Pb/Zn deposits (BAM; p32): We distinguish metamorphic phases
408 rich in otherwise minor metal elements, including Ba, Mn, Pb, and/or Zn, because they
409 feature distinctive mineral assemblages in both contact metamorphic and regional
410 metamorphic contexts (Post 1999; Leach et al. 2005). With 449 species (310 mineral
411 kinds), 375 of which are unique to these environments, these deposits are the most
412 mineralogically diverse of any metamorphic group. Several classic localities, including
413 Broken Hill, Australia (Spry et al. 2008); Franklin, Sussex County, New Jersey (Peters et al.
414 1983; Frondel 1990); Fresno County, California (Alfors et al. 1965); and the Wessel
415 manganese mine, South Africa (Cairncross and Beukes 2013), highlight the role of a few
416 mineral-rich localities in enhancing Earth's mineral diversity. Note, however, that these

417 deposits are volumetrically insignificant compared to regional and contact metamorphic
418 rocks of more common igneous and sedimentary protoliths. Consequently, these
419 uncommon phases do not appear in our lists of metamorphic mineral modes
420 ([Supplementary Table 3](#) and associated [Supplementary Read-Me File 3](#)).

421

422 4. Ophiolites (OPH; p38): Ophiolites incorporate highly altered sequences of mafic and
423 ultramafic rocks from the deep oceanic lithosphere—phases that have been
424 subsequently obducted onto crustal formations. As such, they provide important insights
425 to the mineralogy and petrology of the crust-mantle boundary (Moore 2002; Dilek 2003;
426 Kusky 2004). Ophiolites are documented to hold at least 109 mineral species (96 mineral
427 kinds), some of which resemble those of ocean floor igneous rocks altered by
428 serpentinization. However, we consider them as a separate metamorphic group for their
429 unique subaerial exposures of mantle lithologies, because of the occurrence of the
430 mineralogically distinctive and enigmatic Luobusha ophiolite from the Shannan
431 Prefecture of Tibet (references in Litasov et al. 2019), as well as mineralogically diverse
432 ophiolite localities in the Urals and other localities (references in Litasov et al. 2019).
433 Luobusha is of special interest for its puzzling suite of ultrahigh pressure minerals (e.g.,
434 *diamond* and *moissanite*) that co-occur with dozens of highly reduced phases, including
435 native elements (Al, Cr, Cu, Fe, Ti, W), carbides, nitrides, and phosphides that are unique
436 to this locality (Bai et al. 2011). In addition, the Luobusha occurrence features many PGE
437 metal alloys (including possibly as many as 30 undescribed metal phases) that are
438 associated with chromitite zones reminiscent of assemblages in layered intrusions

439 (references in Litasov et al. 2019; Hazen et al. 2023). We include these diverse, rare
440 minerals under ophiolites, though details of their paragenesis, and especially their
441 assignments to metamorphic processes, remain uncertain (Ballhaus et al. 2017; Litasov
442 et al. 2019).

443 Extensive alteration of Earth's oldest rocks obscures the identity of the oldest
444 ophiolites, which may have predated the Proterozoic Eon, significantly before 2.5 Ga
445 (Kusky et al. 2001; Zhai et al. 2002; Furnes et al. 2007; Nutman and Friend 2007).
446 Confident identifications of several altered ophiolites support an origin by at least 2.5 Ga
447 (Kusky 2004)—an observation consistent with the establishment of some form of plate
448 tectonics by the late Archean Eon.

449

450 5. High-pressure metamorphism (HPM; p39): So-called “high-pressure” metamorphic
451 assemblages are distinguished by their formation in the deep crust and upper mantle
452 under unusually low geothermal gradients of less than 10 °C/km. Such conditions are
453 only possible during transient subduction and subsequent rapid buoyant uplift of crustal
454 rocks (Chopin 1984; Carswell and Compagnoni 2003; Hacker 2006; Palin and White 2016;
455 Zheng and Chen 2017). High-pressure metamorphic rocks include blueschist facies,
456 typically with *glaucophane*, *jadeite*, and/or *lawsonite* (formed at depths to 30 km);
457 eclogite with *omphacite* and *pyrope* (> 45 km); and ultrahigh pressure (UHP) formations,
458 featuring the dense *coesite* form of SiO₂ (> 80 km), *micro-diamond*, and other dense
459 phases that point to origins approaching depths of 200 km. We list 113 high-pressure
460 metamorphic mineral species (89 mineral kinds), of which 29 species, including

461 *barioperovskite* (BaTiO_3), *ellenbergerite* [$\text{Mg}_6(\text{Mg}, \text{Ti}^{4+}, \text{Zr}^{4+}, \square)_2(\text{Al}, \text{Mg})_6\text{Si}_8\text{O}_{28}(\text{OH})_{10}$], and
462 *trinepheline* (NaAlSiO_4), are unique to these metamorphic environments.

463 The ages of the oldest known high-pressure metamorphic rocks (< 850 Ma), and even
464 younger ages for the oldest UHP occurrences (Ganade et al. 2023), reveal much about
465 Earth's evolving lower crust and upper mantle (Jahn et al. 2001; Brown 2007; Stern
466 2018). Thus, for example, several of the oldest recorded *lawsonite* occurrences are from
467 the Paleozoic Era (De Roever 1956). These Neoproterozoic and later developments are in
468 sharp contrast to ultrahigh temperature metamorphic rocks from the Archean and
469 Proterozoic Eons (Brown 2006; Harley 2021). In particular, there are no known examples
470 of blueschist or ultrahigh pressure metamorphism until after 700 Ma (Ernst 1972; Palin
471 and White 2016; Brown and Johnson 2019; Holder et al. 2019). These temporal
472 differences apparently reflect the cooling average geotherm over billions of years of
473 Earth history.

474
475 6. Regional metamorphism (REG; p40): Most metamorphic rocks fall under the broad
476 heading of regional metamorphism, which is associated with burial, alteration, and uplift
477 of thick accumulations of sediments, volcanic rocks, and intrusive igneous lithologies. We
478 list 351 regional metamorphic mineral species, representing 205 mineral kinds, with 151
479 species unique to this paragenesis. Most regional metamorphic minerals derive from
480 common sedimentary and igneous protoliths.

481 Regional metamorphic rocks, which typically formed under an average geothermal
482 gradient of 15 to 30 °C/km (Vernon 2008; Philpotts and Ague 2009), are subdivided into

483 Barrovian index mineral zones based on the appearance of new minerals with increasing
484 temperature and/or pressure: *chlorite*, *biotite*, *garnet*, *staurolite*, *kyanite*, and *sillimanite*,
485 as first outlined by Barrow (1893). Mineral zones also extend to lower pressures, though
486 higher than shallow contact/thermal metamorphism (Miyashiro 1961), as well as to
487 ultrahigh temperature environments (> 900 °C at P < 1.5 GPa; Harley 2021). Goldschmidt
488 (1911) and Eskola (1920) proposed a series of facies of increasing metamorphic grades,
489 originally based on the mineralogy of metabasalt, including greenschist facies (typically
490 with *chlorite*, *epidote*, and *serpentine*), amphibolite facies (*hornblende* and *plagioclase*),
491 and granulite facies (a pyroxene group mineral and *plagioclase*). Subsequent research
492 extended metamorphism to the UHT facies (often with *orthopyroxene*, *osumilite*, and/or
493 *sapphirine*). In this overview we have lumped these regional metamorphic zones, though
494 future research may warrant splitting into multiple groups based on ranges of
495 temperature, pressure, and/or composition. Regional metamorphism, unlike high-
496 pressure metamorphism, was well established by the Neoproterozoic Era (> 2.5 Ga).

497 Regional metamorphic mineral zones may form by either prograde metamorphism
498 during heating and/or burial, or retrograde metamorphism during cooling and/or
499 unburial. If close to equilibrium conditions, metamorphic rocks rarely contain more than
500 4 or 5 major minerals, following Gibbs' phase rule. However, many metamorphic mineral
501 assemblages have more than 6 coexisting major phases and therefore may not represent
502 equilibrium mineral assemblages.

503

504 7. Mantle metasomatism (MET; p41): Deep-seated metasomatism, including processes in
505 both the lower crust and upper mantle (Luth 2003; O'Reilly and Griffin 2012), is a high-
506 pressure process that combines aspects of metamorphism and metasomatism, thereby
507 altering the chemistry of existing ultramafic/mafic minerals and producing new phases
508 through interactions with deep C-O-H fluids (Manning and Frezzotti 2020). We identify
509 37 oxide and silicate mineral species (35 kinds) formed through mantle metasomatism,
510 all but 5 of which (including *nixonite*, Na₂Ti₆O₁₃; Anzolini et al. 2019) are familiar minerals
511 in other environments.

512
513 8. Shear-induced minerals (SHE; p43): Minerals that form while experiencing significant
514 shear strain represent a distinct metamorphic paragenetic mode in our system. Shear-
515 induced mineralization is most commonly associated with the polished fault surfaces
516 known as slickensides that represent zones of mylonitization, typically with pyroxene
517 converted to amphibole and plagioclase much reduced in grain size and spread out into
518 layers (Harker 1950; Passchier and Trouw 2005; Trouw et al. 2009).

519 Such shear zones can also act as fluid conduits (Gates and Speer 2022). Minerals
520 produced by strain/shear can be formed by purely mechanical action, or they may
521 involve chemical changes. Shear phenomena include twinning, as commonly observed
522 with *calcite* in marble; strain bending, for example of mica; inclusion trains; cracks; and
523 recrystallization (Harker 1950).

524 In Supplemental Table 1 we tabulate 30 mineral species (29 kinds) known to form in
525 shear zones, most of which are common oxides and silicates that recrystallize in silicate

526 rocks during shearing. The “sericite” variety of *muscovite* is among the most common
527 mylonite minerals, often in association with *albite*. In other reactions, *biotite* shears to
528 form *chlorite*, at times with *magnetite*; *augite* or *hornblende* shears to *chlorite* plus
529 *epidote* or *calcite*; *forsterite* shears to *tremolite* or *anthophyllite* plus *talc*; *andradite*
530 transforms in part to *titanite* and *magnetite*; and the antigorite form of *serpentine* arises
531 through shearing of other *serpentine* polymorphs. While most of these phases probably
532 first appeared early in Earth’s history, the rare chlorite group mineral *donbassite*
533 $[\text{Al}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2 \cdot \text{Al}_{2.33}(\text{OH})_6]$ has been reported uniquely from slickensides of coal
534 (Anthony et al. 1990–2003), and therefore must have formed within the past 350 million
535 years as a biologically-mediated phase.

536

537 These eight proposed groups of metamorphic rocks, though useful in the larger context of
538 the evolutionary system and its consideration of paragenetic modes writ large, are subjective
539 and fail to properly represent the diversity of metamorphic *P-T-X* environments. Inevitably,
540 significant overlaps occur in the compositional, environmental, mineralogical, and temporal
541 ranges of the eight broad categories of metamorphic rocks outlined above. Nevertheless, we
542 suggest that each group is associated with its own characteristic mineral assemblages and
543 environmental contexts (e.g., Deer et al. 1982-2013; Anthony et al. 1990-2003). Therefore, each
544 of the eight processes plays its own distinctive role in the evolutionary system of mineralogy.

545

546
547
548

3. METAMORPHIC MINERAL ASSOCIATIONS AND NETWORK ANALYSIS

549 Bowen (1928) employed patterns of “mineral associations and antipathies” in the
550 development of his theory of igneous rock evolution, in which he recognized that some pairs of
551 minerals are frequently encountered in equilibrium igneous assemblages, whereas as others
552 never occur (Hazen et al. 2023). The same principles apply to metamorphic minerals, with the
553 caveat that overlapping prograde and retrograde reactions often result in nonequilibrium
554 assemblages.

555 In this section we amplify Bowen’s approach by quantifying the extent of coexistence among
556 pairs and larger groupings of 94 of the commonest minerals in metamorphic rocks (Table 3;
557 Appendix 1). Of these metamorphic minerals, 66 are silicates, 14 are oxides or hydroxides, 8 are
558 carbonates or phosphates, 4 are sulfides, and 2 are polymorphs of carbon. Collectively, these 94
559 minerals incorporate 23 different essential chemical elements, including oxygen (in 88 of 94
560 minerals), Si (71), Al (44), Fe (40), Ca (38), Mg (37), H (27), Na (14), C (10), F (8), K (8), Ti (7), S
561 (5), Cl (4), Cr (3), Mn (2), Zr (2), and B, Ce, Cu, Ni, P, and Sr (all in only 1 of 94 minerals).

562 The core data of this study are found in Supplementary Table 3 (see also Supplementary
563 Read-Me File 3), which details the distribution of these 94 metamorphic minerals among 2785
564 metamorphic rock modes. We employed 29 primary sources to assemble these metamorphic
565 mineral modes: Augustithis (1985; 156 modes), Botha (1983; 95 modes), Carswell (1990; 198
566 modes), Carswell and Compagnoni (2003; 49 modes), Coleman et al. (1965; 13 modes), Grapes
567 (2006; 218 modes), Harker (1950; 285 modes); Harley (2021; 121 modes); Joplin (1968; 345
568 modes); Philpotts and Ague (2009; 885 modes); Reverdatto and Sόbolev (1973; 71 modes); and
569 Tilley et al. (1964; 50 modes), as well as 299 modes from contributions by Ferry and colleagues

569 (Davis and Ferry 1983; Ferry 1976, 1984, 1988, 1989, 1992, 1994, 1995, 1996, 2007; Ferry and
570 Rumble 1997; Ferry et al. 1987, 2001, 2002, 2005; Léger and Ferry 1993; Penniston-Dorland and
571 Ferry 2006).

572 Ideally, the extensive data on coexisting metamorphic minerals in Supplementary Table 3
573 would represent a wide range of equilibrium assemblages, while accurately documenting the
574 relative abundances of metamorphic minerals. However, even though we have surveyed 29
575 diverse compilations of metamorphic modes representing several geographic areas and most
576 distinct types of metamorphic environments, it is important to recognize at least four likely
577 sources of bias and error in the modal mineralogy data in Supplementary Table 3. Each of these
578 factors may distort the true distribution of mineral associations among metamorphic rocks.

579 (1) *Biases owing to disequilibrium*: Metamorphic mineral modes often represent non-
580 equilibrium assemblages, with prograde and retrograde phases of differing metastability
581 occurring together. Therefore, the coexistence data in Supplementary Table 3 cannot be
582 employed in the same way as the corresponding table of igneous modes in Part VII of this
583 series.

584 (2) *Biases related to optical petrography*: Most of our modal data come from studies that
585 employed optical petrography, but not electron microprobe analysis. Several inevitable biases
586 result.

587 • Euhedral vs. poorly crystallized phases: Well-crystallized minerals such as almandine
588 or staurolite are more likely to be identified than fine-grained assemblages
589 containing brucite, phyllosilicates, or zeolites. For example, Ferry (1994), Ferry and
590 Rumble (1997), and Ferry et al. (2002) document the widespread occurrence of

- 591 brucite and serpentine—metamorphic minerals almost never recorded in modes
592 from earlier literature.
- 593 • Exotic versus common minerals: Our compilation likely over-represents certain rare
594 minerals, such as *coesite* and *diamond*, especially if they occur in optically distinctive
595 crystals.
 - 596 • Optically similar minerals: A number of minerals are difficult to identify via optical
597 petrography. For example, distinguishing among *calcite*, *ankerite*, and *aragonite*, as
598 well as between fine-grained *quartz/albite* and *muscovite/paragonite*, is difficult and
599 may lead to errors in reported modes.
 - 600 • *Opaque minerals*: Identification of opaque minerals is another petrographic challenge
601 that leads to omissions and biases in Supplementary Table 3. For example, electron
602 microprobe analyses indicate that *pyrrhotite* is extremely common in a wide variety
603 of metamorphic rocks (e.g., Ferry 1994), though it is often unreported (or perhaps
604 misidentified as *pyrite*) in earlier descriptions of metamorphic rock modes. Similarly,
605 some opaque Fe-Ti-Cr bearing oxides, including the oxide spinels *chromite* and
606 *hercynite*, as well as *ilmenite*, and *rutile*, may be under-represented in our
607 tabulations.
 - 608 • Trace minerals: Detailed studies with electron microprobe analysis suggest that
609 minor phases, especially those with grain sizes < 5 micrometers, are much more
610 common than suggested by our survey. Examples of rarely reported trace
611 metamorphic minerals include *allanite* and *monazite* (Wing et al. 2003); *baddelyite*,

612 *geikielite, qandilite, and sphalerite* (Ferry 1996); and *anhydrite, calzirtite, and*
613 *celestine* (Ferry et al. 2002).

614 (4) *Problems in nomenclature*: A number of petrographic terms lead to ambiguities when
615 listing minerals in Supplementary Table 3. General group names such as “garnet” encompass
616 several different mineral kinds in our study. Therefore, the relative abundances of *almandine,*
617 *andradite, grossular, and pyrope* may be in error. “Spinel” may refer to the mineral species
618 MgAl_2O_4 , or to members of the oxide spinel group such as *magnetite, chromite, or hercynite.*
619 “Ankerite” is technically $\text{CaFe}(\text{CO}_3)_2$, but is often used to designate a Fe-bearing dolomite in the
620 literature of metamorphic petrology.

621 (5) *Missing recent research*: Metamorphic studies of the past 20 years are less likely to
622 tabulate numerous modes; fewer than a third of the modes in Supplementary Table 3 were first
623 published after 2003. As a consequence, our survey under-represents more recently
624 documented metamorphic lithologies, such as ultrahigh temperature metamorphism (Harley
625 2021).

626

627 *Metamorphic mineral coexistence*: Of the 94 minerals considered in Supplementary Table 3, 21
628 occur commonly in several different types of metamorphic rocks and therefore are not easily
629 grouped by community detection algorithms. Therefore, we tabulated the frequency of co-
630 occurrence of every pairwise combination of the remaining 73 mineral kinds, all of which are
631 more likely to be associated with only one or two metamorphic lithologies (Supplementary
632 Table 4; see also associated Supplementary Read-Me File 4). For each mineral pair we
633 calculated the percentage of the less common mineral that co-occurs with the more common

634 mineral (Supplementary Table 5; see also Supplementary Read-Me File 5). For example,
635 consider matrix element W7, which relates to the coexistence of *andalusite* (with 146
636 occurrences, as listed in Supplementary Table 4) and *cordierite* (with 395 occurrences). In
637 Supplementary Table 4, matrix element W7 reveals that 84 rocks (out of 2785 tabulated)
638 contain both *andalusite* and *cordierite*. Therefore, in Supplementary Table 5, matrix element F7
639 = $84/146 \times 100 = 58 \%$.

640 This protocol is especially important when considering the coexistence of a relatively rare
641 mineral with a common one. For example, *baddeleyite* is a scarce metamorphic mineral,
642 occurring in only 18 of 2785 metamorphic rocks recorded in Supplementary Table 3. However,
643 16 of those occurrences also contain the common metamorphic mineral *calcite*. Therefore, as
644 recorded in matrix element Q14 of Supplementary Table 5, $16/18 = 89 \%$ of *aegirine*
645 occurrences also have *calcite*. Thus, *baddeleyite/calcite* is a common mineral pair whenever the
646 rare mineral *baddeleyite* occurs. As Bowen emphasized for igneous minerals (Bowen 1928;
647 Hazen et al. 2023), we find that a small percentage of all possible metamorphic mineral pairs
648 commonly occur (e.g., *almandine/biotite*; *diopside/grossular*; *chloritoid/muscovite*;
649 *quartz/staurolite*).

650 As demonstrated in our previous study of igneous minerals (Hazen et al. 2023), network
651 analysis of mineral associations and antipathies reveals phase relationships and reaction
652 sequences that may not be immediately recognized from tables of mineral modes. Therefore,
653 we have applied two types of data visualization: unipartite networks that highlight Louvain
654 community detection and bipartite networks representing relationships among minerals and
655 their formational environments.

656

657 *Unipartite networks and Louvain community detection analysis of coexisting metamorphic*

658 *minerals*: Mineral network analysis reveals patterns among coexisting minerals (Morrison et al.

659 2017). Accordingly, **Figures 1A and 1B** display a unipartite network that illustrates the

660 coexistence among 73 relatively common metamorphic minerals, as listed in Table 3. This graph

661 was built on “Observable” (<https://observablehq.com/>), using D3js (Bostock et al. 2011). The

662 networks use the D3-force algorithm ([https://d3-wiki.readthedocs.io/zh_CN/master/Force-](https://d3-wiki.readthedocs.io/zh_CN/master/Force-Layout/)

663 [Layout/](https://d3-wiki.readthedocs.io/zh_CN/master/Force-Layout/)) for its network layout. The code and an interactive version of this network can be

664 found at: ([https://observablehq.com/@anirudhprabhu/revised-evolutionary-system-of-mineralogy-](https://observablehq.com/@anirudhprabhu/revised-evolutionary-system-of-mineralogy-part-8-uni)

665 [part-8-uni](https://observablehq.com/@anirudhprabhu/revised-evolutionary-system-of-mineralogy-part-8-uni); for instructions, see Figure 1 caption).

666 Each of the 73 nodes in Figure 1 represents a metamorphic root mineral kind, with the size

667 of the node in Figure 1A indicating the abundance of that mineral in our tabulations of 2785

668 metamorphic rock modes (Supplementary Table 3). Links between pairs of nodes indicate

669 mineral coexistence. in Figure 1A, we illustrate the case where at least 6 % of occurrences of

670 the less common mineral coexist with the more common mineral, based on percentages

671 tabulated in Supplementary Table 5 (6 % is the highest percentage for which all 73 mineral

672 nodes are still interconnected). Figure 1 is a static rendering of a dynamic interactive network in

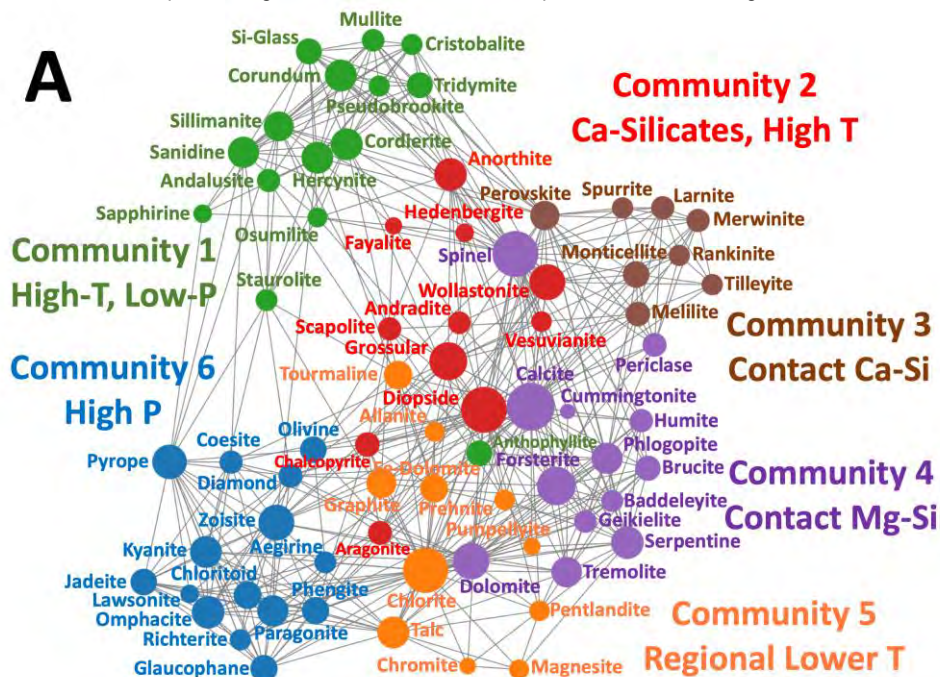
673 which the co-occurrence percentage, P , can be varied continuously from 1 to 100 %. This

674 variable feature, as well as other interactive aspects of the online version of Figure 1, facilitates

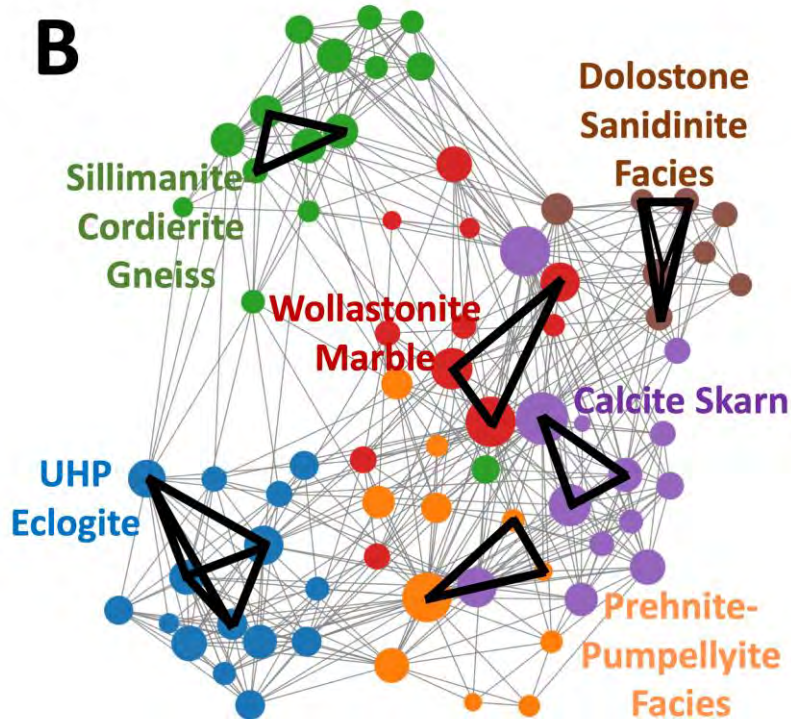
675 studies of mineral associations and antipathies.

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679

680 **Figure 1.** (A) A unipartite network of 73 common metamorphic minerals (colored circles), with links
 681 between pairs of coexisting minerals. Node sizes indicate the relative abundances of the minerals, while
 682 colors indicate 6 communities of metamorphic minerals that were determined using Louvain community

683 detection (see text). Each of these communities corresponds to a different temperature-pressure-
684 composition regime. In this figure, links are drawn between two minerals if at least 6 % of rocks that
685 incorporate the less common mineral also incorporate the more common mineral (as tabulated in
686 Supplementary Table 3). One can vary this percentage in an interactive version of this graph at:
687 (<https://observablehq.com/@anirudhprabhu/revised-evolutionary-system-of-mineralogy-part-8-uni>).
688 Hover your cursor over any node to identify the corresponding mineral; click and hold your cursor to
689 move that node and identify links to other nodes; use your cursor to move the “Weight Threshold”
690 vernier to systematically eliminate links between nodes based on *P* values (see text). Adjust node
691 attributes by clicking on the “Size Nodes By” feature. **(B)** The unipartite network of 73 metamorphic
692 minerals embeds metamorphic rock types as sub-graphs. Highlighted subgraph examples include 6
693 common metamorphic lithologies.

694

695 Links in a mineral network are not uniformly distributed; they typically display sub-networks
696 of more closely connected nodes. We color mineral nodes in Figure 1 based on Louvain
697 community detection analysis (Girvan and Newman 2002; Fortunato 2010), which employs a
698 heuristic method based on modularity optimization to extract the community structure of large
699 networks (Blondel et al. 2008). This method identifies members of a group iteratively in two
700 phases: (1) starting with each node as its own distinct community, larger communities are
701 formed at a local level by maximizing modularity of certain nodes; (2) each small community is
702 aggregated into one “super node” to form a new “super node network.” We repeat these steps
703 until the modularity has been optimized and there are no changes in the network. The Louvain
704 modularity approach reveals an optimal number of communities without requiring the user to
705 specify the number of clusters in a dataset. Consequently, Louvain community detection

706 removes some of the bias associated with some other clustering algorithms, while identifying
707 the most closely interconnected subsets of minerals.

708 The identification of community structures may be complicated by the inclusion of mineral
709 nodes that link to multiple communities. Such nodes typically plot near the center of a network
710 and “pull” more diagnostic nodes toward the middle while obscuring community structures
711 (Hazen et al. 2023). Therefore, we do not include 21 of the most common metamorphic
712 minerals in our networks, including such major phases as *albite*, *almandine*, *augite*, *biotite*,
713 *hornblende*, *kspars*, *muscovite*, *plagioclase*, and *quartz*, because they occur across a wide variety
714 of metamorphic rocks. In addition, *apatite*, *ilmenite*, *magnetite*, *pyrite*, *pyrrhotite*, *rutile*, *titanite*
715 and *zircon* are widespread accessory phases that we exclude from network analysis. By
716 contrast, each of the 73 metamorphic minerals illustrated in Figure 1 is more characteristic of a
717 restricted pressure, temperature, and/or compositional metamorphic regime. One
718 consequence of this exclusion of 21 of the most widespread metamorphic minerals is that the
719 classic Barrovian sequences of metapelite and metabasite zones are not well represented in
720 Figure 1. Rather, the subset of 73 less ubiquitous phases define six principal communities of
721 metamorphic phases, each with its own distinctive pressure-temperature-composition regime
722 (see also Table 3):

723

724 Community 1: Community 1 holds 15 high-temperature, low-pressure minerals, including
725 such pyrometamorphic and ultra-high temperature phases as *corundum*, *mullite*,
726 *osumilite*, *sanidine*, *sapphirine*, *silicate glass*, *sillimanite*, and *tridymite*, with mineral
727 assemblages typical of pyroxene hornfels, sanidinite, and ultrahigh temperature

728 metamorphism. Community 1 is well separated from most minerals of Communities 2
729 through 6, which represent higher pressure and/or lower temperature environments.
730 Note that within the adjacent Communities 2 and 6, the higher-temperature minerals
731 appear closest to Community 1 in Figure 1. Thus, there is a temperature gradient from
732 upper left to lower right in the network.

733 Community 2: Community 2 features 11 minerals, including *andradite*, *anorthite*, *diopside*,
734 *grossular*, *hedenbergite*, *vesuvianite*, and *wollastonite*, all of which are typical of mid- to
735 high-temperature contact and regional metamorphism of calc-silicates. Note that
736 Communities 2 and 5 display significant overlaps in this network, with a prominent
737 temperature gradient from the top to the bottom of the network. Communities 2 and 5
738 are thus relatively dispersed compared to Communities 1, 3, 4, and 6

739 Community 3: The eight minerals of Community 3—*larnite*, *melilite*, *merwinite*, *monticellite*,
740 *perovskite*, *rankinite*, *spurrite*, and *tilleyite*—form a tightly clustered group of idiosyncratic
741 phases typical of the highest temperature Ca-rich skarns. A number of petrologists have
742 recognized sequences of metamorphic skarn minerals as a function of temperature and
743 composition (Bowen 1940; Harker 1950; Tilley 1951). For example, Bowen (1940) listed
744 10 minerals in order of their increased temperature of formation: *tremolite*, *forsterite*,
745 *diopside*, *periclase*, *wollastonite*, *monticellite*, *åkermanite* (e.g., *melilite*), *spurrite*,
746 *merwinite*, and *larnite*, whereas subsequent studies slightly rearranged the order of some
747 of these phases (e.g., Weeks 1956; Ferry 1976). We see suggestions of such a sequence,
748 with the highest temperature phases in Community 2 located in the upper right of Figure
749 1.

750 Community 4: Thirteen minerals, including Mg-bearing *brucite*, *cumingtonite*, *dolomite*,
751 *forsterite*, *geikielite*, *humite*, *periclase*, *phlogopite*, *serpentine*, *spinel*, and *tremolite*,
752 represent contact metamorphic environments of Mg-rich skarns, as well as regional
753 metamorphism of Mg-Si-silicates. Mineral assemblages of Community 4 thus have close
754 links to the higher temperature, more calcic environments of Communities 2 and 3.

755 Community 5: Community 5 incorporates 11 metamorphic minerals, including phases from
756 two distinct environments. On the one hand, lower-temperature regional metamorphic
757 lithologies are represented by *chlorite*, *prehnite*, and *pumpellyite*, which are characteristic
758 of the prehnite-pumpellyite and greenschist facies. Community 5 also includes a suite of
759 minerals typical of ophiolites and metamorphosed ultramafic rocks, including *chlorite*,
760 *chromite*, *magnesite*, *pentlandite*, and *talc*. Consequently, Community 5 is relatively
761 dispersed and co-mingled with the higher temperature phases of Community 2.

762 Community 6: Diagnostic high-pressure metamorphic phases occur in Community 6. This
763 well-defined cluster of 15 minerals in the lower lefthand region of Figure 1 holds typical
764 high-pressure phases of blueschist (*glaucophanite*, *lawsonite*), eclogite (*jadeite*, *kyanite*,
765 *omphacite*), and ultrahigh pressure (*coesite*, *diamond*, *pyrope*) facies. These minerals are
766 all characteristic of metamorphism under the relatively low geothermal gradients
767 experienced by deeply subducted crustal wedges that buoyantly rebound.

768
769 The degree of connectivity, or network density, of the graph in Figure 1 varies significantly
770 with the percentage of co-occurrence, P . The density of a network (D) is defined as the fraction
771 of all possible links that are observed; in the case of 94 minerals, there exist $[(94^2 - 94)/2] =$

772 4371 possible links. When $P = 1\%$, the density of the network has a value of $D = 0.400$ because
773 1747 (40.0 %) of the 4371 possible links between mineral pairs are observed to occur at least
774 once. By contrast, when we restrict links to $P = 25\%$ then 524 links remain ($D = 0.120$). And
775 when we consider $P = 50\%$, only 198 links persist – a relatively sparse network with $D = 0.045$.

776 Note that at $P > 6\%$, one or more mineral nodes is no longer connected to the network. The
777 first node to disconnect is *cumingtonite* at $P = 7\%$, while at $P = 15\%$ *olivine* also becomes
778 disconnected. At $P = 25\%$, 66 of the original 73 mineral nodes remain interconnected, including
779 representatives of all 6 communities. However, at $P = 50\%$, only 39 nodes form a sparse
780 network with all 13 minerals of Community 4 (Mg skarns) forming a hub with radiating suites of
781 minerals from Community 2 (7 minerals), Community 3 (6 minerals), and Community 5 (10
782 minerals). By contrast, all but 2 minerals from Community 6 and 1 mineral from Community 1
783 remain connected at $P = 50\%$.

784 An important feature of the unipartite networks of metamorphic minerals is that every
785 metamorphic rock, for example each of the 2785 examples in Supplementary Table 3, as well as
786 every prograde or retrograde sequence of metamorphic rocks, is embedded as a multi-node
787 subgraph of this network (Figure 1B). P - T - X series of lithologies can be represented by a
788 sequence of subgraphs that wend their way across the larger network of Figure 1B. Thus, Figure
789 1 and related networks are useful visual approaches to comparing and contrasting aspects of
790 metamorphic petrology for research and education.

791 In many respects, the topology of Figure 1 for common metamorphic minerals is reminiscent
792 of the topology of the analogous network of 115 igneous minerals in Part VII of this series
793 (Hazen et al. 2023; their Figure 1). In both instances, Louvain community detection reveals

794 several communities of mineral kinds, each from a distinct compositional and/or environmental
795 regime. Furthermore, every rock in extensive lists of mineral modes is represented by a
796 subgraph (compare Figure 1B to Hazen et al. 2023, their Figure 1B). Nevertheless, two
797 important differences exist between these two renderings.

798 1. In the case of igneous rocks, the majority of the minerals tabulated by Hazen et al. (2023)
799 are minor accessory phases (< 5 vol %), most of which incorporate relatively rare
800 elements. By contrast, reported modes of metamorphic rocks rarely include minor
801 phases. Consequently, the network for metamorphic minerals illustrates fewer mineral
802 kinds, but almost twice as many major phases spanning a much wider *P-T* range,
803 compared to the network for igneous mineral kinds.

804 2. In our study of the evolution of igneous minerals, we attempted to include only modes
805 based on equilibrium assemblages of primary minerals. Accordingly, we have suggested
806 that phase equilibrium for multi-component chemical systems (including myriad rare
807 elements) might be extracted from the topology of the igneous mineral network.
808 However, owing to often incomplete transformations during prograde or retrograde
809 metamorphism, the assumption of equilibrium assemblages cannot be applied to
810 metamorphic rocks. On the other hand, because most metamorphic rock modes are
811 embedded in Figure 1, it should be possible to illustrate any metamorphic sequence in *P-*
812 *T-X* space with an animated series that systematically moves across Figure 1, even if the
813 individual mineral assemblages are not in equilibrium.

814

815 Unipartite network graph at $P = 33\%$: The unipartite graph of Figure 1 represents the co-
816 occurrences of 73 different metamorphic minerals based on tabulations of 2785 modes at $P = 6$
817 %, which is the maximum value at which all minerals are still connected. However, Figure 1 may
818 be visually misleading in three ways.

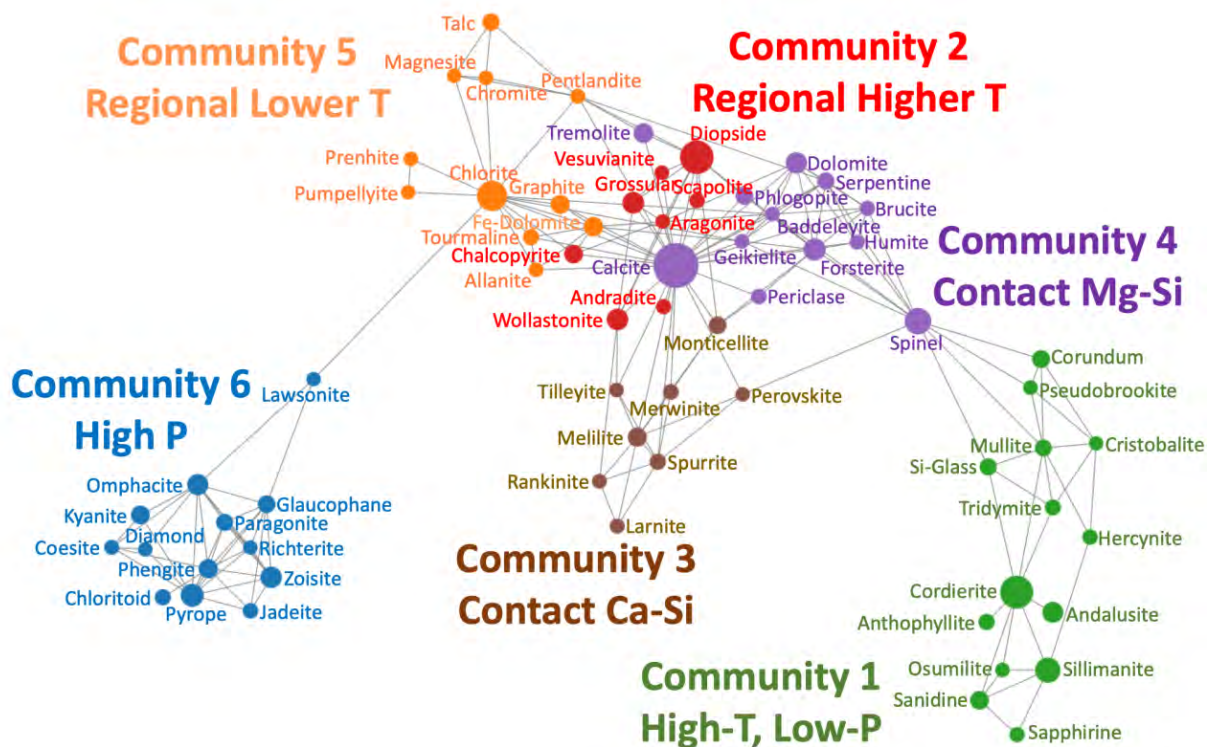
819 First, Figure 1 is a two-dimensional projection of a graph in 72 dimensions [any network with
820 N nodes possesses $(N - 1)$ dimensions]. Consequently, the proximity of two adjacent nodes
821 does not necessarily imply that those two minerals are closely related. Thus, for example,
822 *forsterite* (Community 4) and *prehnite* (Community 5) lie next to each other in Figure 1, yet
823 those two minerals do not coexist in any rock in our survey.

824 Second, in some instances a mineral will be located in a position somewhat removed from its
825 community. For example, the Mg-amphibole *anthophyllite* is included in Community 1, yet it
826 appears near the center of Figure 1, closer to Communities 2, 4, and 5. This positioning results
827 from *anthophyllite's* close association with both *cordierite* (Community 1) and *forsterite*
828 (Community 4)—a common situation when one node is closely associated with two or more
829 communities.

830 Third, because Figure 1 represents all links between nodes with at least 6 % co-occurrence,
831 some relatively weak connections (i.e., those with only 6 % to 10 % co-occurrence) will tend to
832 intermingle some phases that only co-exist relatively infrequently with other minerals in two or
833 more communities.

834 **Figure 2** is a unipartite network similar to that of Figure 1 but with $P = 33\%$. Therefore, a link
835 appears only if at least one-third of occurrences of the rarer mineral also features the more
836 common mineral. The result is a much sparser network of 66 mineral nodes and 185 links.

837 Seven minerals—*aegirine*, *anorthite*, *cummingtonite*, *fayalite*, *hedenbergite*, *olivine*, and
838 *staurolite*—are no longer connected. The resulting graph retains the six communities of Figure
839 1, but they are much more tightly clustered, revealing well-separated groups of minerals.



840 **Figure 2.** A unipartite network of 66 common metamorphic minerals (colored circles). Node sizes
841 indicate the relative abundances of minerals, while colors indicate six communities of metamorphic
842 minerals that were determined using Louvain community detection (see text). Each of these
843 communities corresponds to a different temperature-pressure-composition regime. In this figure, links
844 are drawn between two minerals if at least 33 % of rocks that incorporate the less common mineral also
845 incorporate the more common mineral (as tabulated in Supplementary Table 3). One can vary this
846 percentage in an interactive version of this graph at:
847 <https://observablehq.com/@anirudhprabhu/revised-evolutionary-system-of-mineralogy-part-8-uni>.
848
849 Hover your cursor over any node to identify the corresponding mineral; click and hold your cursor to
850 move that node and identify links to other nodes; use your cursor to move the “Weight Threshold”
851 vernier to systematically eliminate links between nodes based on *P* values (see text). Adjust node
852 attributes by clicking on the “Size Nodes By” feature.

853 Figure 2 displays the same six communities (with 66 of the 73 minerals) that appear in Figure
854 1. However, the more stringent criteria of $P = 33\%$ results in a network with far greater
855 separation between communities. Community 1 now appears at the extreme right of the graph,
856 retaining 14 of the original 15 minerals (only *staurolite* has been lost). The only link between
857 Community 1 and the rest of the network is to Community 4 through *spinel*.

858 Community 4 has 12 of the original 13 minerals (*cumingtonite* disconnects at $P = 7\%$),
859 which form a cluster in the upper right of the network. Note that *tremolite* is displaced from the
860 main cluster because it forms only three links—to *calcite* (also in Community 4), *diopside*
861 (Community 2), and *pentlandite* (Community 5). Community 4 is most closely linked to
862 Communities 2 and 5, but has only 3 links to Community 3, 1 link to Community 1, and no
863 connections to Community 6.

864 Community 3, which represents relatively high-temperature skarn minerals, retains all of its
865 original 8 phases in an isolated cluster that is linked only to the lower-temperature skarn
866 minerals of Communities 2 and 4. By contrast, Community 2 is the most intermingled cluster in
867 this network. Only 8 of the original 11 minerals remain; *anorthite*, *fayalite*, and *hedenbergite*
868 are disconnected by $P = 25\%$.

869 All 11 of the original Community 5 minerals appear in Figure 2, which reveals a well-defined
870 cluster with three subgraphs. *Chlorite-prehnite-pumpellyite* appear as a triangle corresponding
871 to low-temperature metamorphism, while *chromite-magnesite-pentlandite-talc* form a quartet
872 of ophiolite phases. In addition, *allanite*, *Fe-dolomite*, *graphite*, and *tourmaline* are commonly
873 associated accessory minerals in regional metamorphic rocks. Community 6, with 13 of the
874 original 15 high-pressure minerals (minus *aegirine* and *olivine*), is the most isolated cluster in

875 Figure 2, with only a single link between *lawsonite* of Community 6 and *chlorite* of Community
876 5.

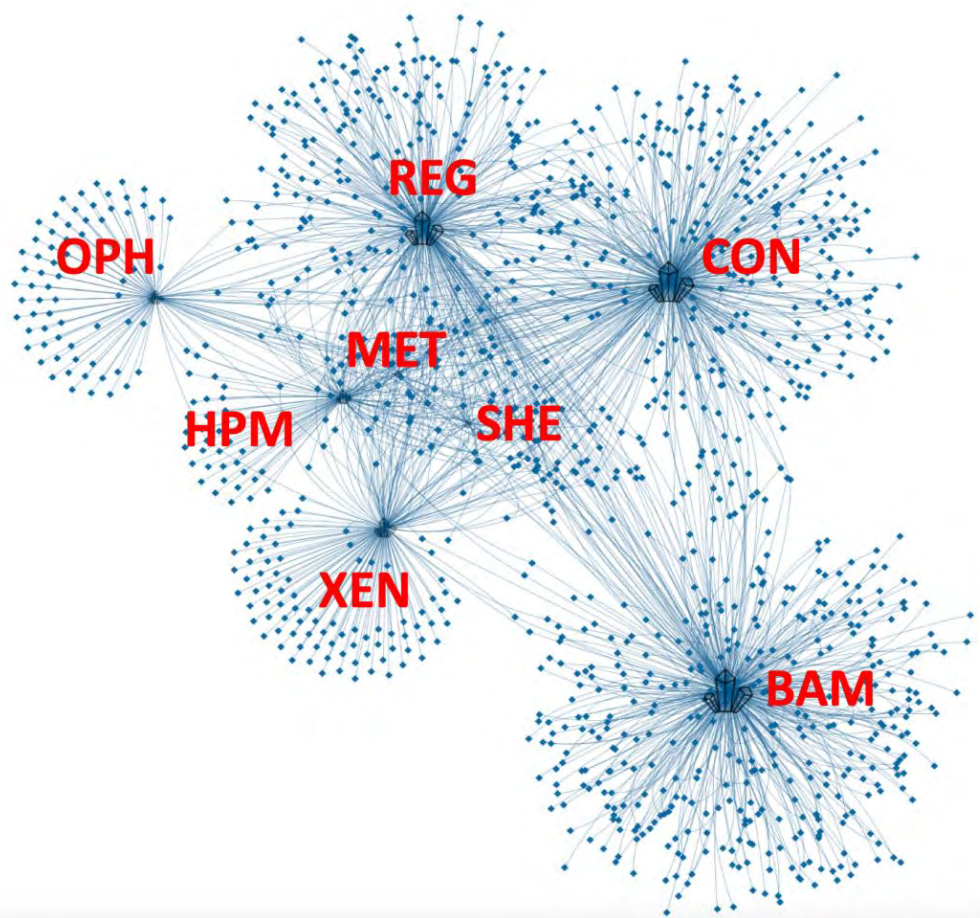
877 The resulting sparse network forms an arc, with the highest pressure minerals to the left and
878 the lowest pressure minerals to the right. The central grouping of Communities 2, 3, and 4
879 represent metamorphosed Ca-Mg silicates and skarns, with higher temperature phases located
880 toward the bottom of the graph. Thus, in spite of the continuous variations of temperature,
881 pressure, and composition represented by metamorphic mineral assemblages, distinct clusters
882 representing formational environments with idiosyncratic minerals are important
883 characteristics of metamorphic rocks.

884 An unexpected result of this network analysis are the strong separations among some mineral
885 communities. By their nature, metamorphic rocks represent continua of *P-T-X* conditions. One
886 might expect, therefore, to observe similarly continuous linkages in the network topology of
887 Figure 2. However, we observe strong clustering into six communities with significant gaps.
888 Most notably, Community 1 on the right and Community 6 on the left are isolated from
889 Communities 2 through 5. In addition, we observe lesser gaps between Communities 2 and 5,
890 as well as between Communities 3 and 4. Similar topologies in network graphs of igneous rocks
891 correspond to known compositional trends, such as the Daly gap (Daly 1925; Hazen et al. 2023,
892 their Figure 5). Is it possible that similar composition gaps exist among the diversity of
893 metamorphic rocks?

894

895 *Bipartite network of metamorphic minerals and their host lithologies:* Figure 3 is a bipartite
896 network (i.e., a network with links between two different kinds of nodes) that illustrates 1220

897 diamond-shaped nodes representing metamorphic mineral species and their 1686 links to 8
898 nodes that represent the different groups of metamorphic rocks, as first described by Hazen
899 and Morrison (2022) and modified here in Supplementary Table 1. This bipartite network was
900 made using the “visNetwork” (Almende et al. 2021) and “igraph” (Csardi & Nepusz 2006) R
901 packages. The code for construction of this network can be found
902 at: <https://github.com/anirudhprabhu/StellarNet/tree/master/PartVIII>. The network layout
903 uses the “barnesHut” approximation algorithm (Barnes and Hut 1986).



904

905 **Figure 3.** This bipartite network of 1220 metamorphic minerals (colored diamond-shaped nodes)
906 displays 1686 links to 8 icons representing different major groups of metamorphic rocks, as first
907 described by Hazen and Morrison (2022) and modified here (Table 2; Supplementary Table 1).
908 Three-letter identifiers are XEN = pyrometamorphism of xenoliths (with 173 minerals); CON =

909 contact metamorphism (424); BAM = metamorphic Ba/Mn/Pb/Zn deposits (449); OPH =
910 ophiolites (109); HPM = high-pressure metamorphism (113); REG = regional metamorphism
911 (351); MET = mantle metasomatism (37); and SHE = shear-induced minerals (30). The 6
912 “starburst” features around the periphery reflect 959 mineral species that are uniquely
913 associated with only one paragenetic mode. Most of the other nodes, representing 261 mineral
914 species that are connected to two or more nodes representing paragenetic modes, lie in the
915 dense central region of the bipartite network.
916

917 This bipartite network displays several features that are common to other mineral systems
918 (Morrison et al. 2017, 2020, 2022; Hazen et al. 2019). A minority of 261 relatively common
919 metamorphic mineral species adopt central positions, where each is linked to two or more
920 different groups of metamorphic minerals. Only 1 mineral species, *magnetite*, is linked to all 8
921 groups of metamorphic rocks. Six additional common minerals—*calcite*, *diopside*, *ilmenite*,
922 *pyrite*, *rutile*, and *quartz*—are linked to 7 groups. These minerals from multiple metamorphic
923 lithologies are less diagnostic in defining communities or clusters of closely-related minerals
924 than minerals known from only one or two types of metamorphic rocks.

925 By contrast, a significant majority of mineral species are rare; 959 of these minerals are
926 linked to a single metamorphic mineral group, thus creating six dramatic “starbursts” of nodes
927 decorating the periphery of the bipartite network. Metamorphosed Ba-Fe-Mn-Pb deposits
928 (node BAM) boast the greatest number of these single-node phases (375 species, or 31 % of the
929 1220 metamorphic minerals), which create the largest such display in the lower right of the
930 network. Note that this concentration of relatively rare minerals, like the BAM node with which
931 it is associated, forms a relatively isolated region of the bipartite network. Other prominent
932 starbursts are connected to contact metamorphism (CON; 241 unique mineral species),
933 regional metamorphism (REG; 151 unique species), xenoliths (XEN; 87 unique species), and

934 ophiolites (OPH; 69 unique species). Thus, as in many other mineral systems, most
935 metamorphic minerals are rare, known from 5 or fewer localities and formed by a single
936 process (Hazen and Ausubel 2016).

937 In addition, 160 minerals are associated with exactly two of the 8 metamorphic rock groups,
938 32 minerals are linked to 3 groups, and 30 minerals are linked to 4 groups. The most common
939 connection from one mineral species to two metamorphic rock groups is for contact and
940 regional metamorphic rocks (135 minerals), which explains the proximity of CON and REG
941 nodes in the upper half of Figure 3. Other strong connections of a mineral to two groups of
942 metamorphic rocks include regional and high-pressure metamorphic rocks (71 species);
943 xenolith and contact metamorphic rocks (67 species); xenolith and regional metamorphic rocks
944 (64 species); contact and high-pressure metamorphic rocks (55 species); regional and Ba-Mn
945 deposits (47 species), and contact and Ba-Mn deposits (41 species). These varied mineral
946 associations across several kinds of metamorphic lithologies are reflected in the distinctive
947 topology of Figure 3.

948

949

4. IMPLICATIONS: THE EVOLUTION OF METAMORPHIC MINERALS

950

Metamorphic rocks display characteristics of an evolving chemical system, with significant

951

increases in diversity and average chemical complexity over 4.5 billion years of Earth history

952

(Krivovichev et al. 2018). Tabulations of the earliest known ages for diagnostic metamorphic

953

minerals have the potential to document these changes. The Mineral Evolution Database (MED:

954

<https://rruff.info/evolution>, accessed 11 September 2023) records the ages of 200,000

955

mineral/locality pairs. While ages of metamorphic minerals were not the principal focus of the

956

MED, most major metamorphic minerals are represented by multiple ages. Accordingly, **Table 4**

957

lists the oldest MED ages for 47 minerals that are most commonly found in metamorphic rocks.

958

Table 4. Oldest recorded ages of 47 select metamorphic minerals arranged chronologically.

959

Ages are from the Mineral Evolution Database (<https://rruff.info/evolution>, accessed 11

960

September 2023) unless otherwise noted.

961

962

963

Mineral Kind	Chemical Formula	Age Range (Ma) ¹	Community ²
<i>Geikielite</i>	MgTiO ₃	4330—4310	4
<i>Diopside</i>	CaMgSi ₂ O ₆	4330—4010	2
<i>Hedenbergite</i>	CaFe ²⁺ Si ₂ O ₆	4330—4010	2
<i>Wollastonite</i>	CaSiO ₃	4330—4010	2
<i>Andalusite</i>	Al ₂ SiO ₅	4000—3200	1
<i>Anthophyllite</i>	□Mg ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂	4000—3200	1
<i>Cordierite</i>	(Mg,Fe ²⁺) ₂ Al ₄ Si ₅ O ₁₈	4000—3200	1
<i>Tremolite</i>	□Ca ₂ (Mg _{5.0-4.5} Fe ²⁺ _{0.0-0.5})Si ₈ O ₂₂ (OH) ₂	4000—3200	4
<i>Chloritoid</i>	Fe ²⁺ Al ₂ O(SiO ₄)(OH) ₂	4000—3040	6
<i>Grunerite</i>	□Fe ²⁺ ₂ Fe ²⁺ ₅ Si ₈ O ₂₂ (OH) ₂	4000—2920	--
<i>Cumingtonite</i>	□Mg ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂	4000—2917	4
<i>Kyanite</i>	Al ₂ SiO ₅	4000—2714	6
<i>Sillimanite</i>	Al ₂ SiO ₅	3640—3200	1
<i>Graphite</i>	C	3640—3200	5
<i>Corundum</i>	Al ₂ O ₃	3640—3040	1
<i>Diamond</i> ³	C	3600—3600	6
<i>Spessartine</i>	Mn ²⁺ ₃ Al ₂ Si ₃ O ₁₂	3293—2874	--
<i>Phlogopite</i>	[[KMg ₂ (Mg,Fe ²⁺)(Si,Al) ₂ Si ₂ O ₁₀ (OH,F) ₂]]	3200—3200	4
<i>Grossular</i>	Ca ₃ Al ₂ Si ₃ O ₁₂	2969—2969	2
<i>Vesuvianite</i>	(Ca,Na) ₁₉ (Al,Mg,Fe) ₁₃ (SiO ₄) ₁₀ (Si ₂ O ₇) ₄ (OH,F,O) ₁₀	2918—2835	2

983

984

985

986	<i>Staurolite</i>	$\text{Fe}^{2+}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$	2906—2730	1
987	<i>Piemontite</i>	$\text{Ca}_2\text{Al}_2\text{Mn}^{3+}(\text{Si}_2\text{O}_7)(\text{SiO}_4)\text{O}(\text{OH})$	2906—2782	--
988	<i>Prehnite</i>	$\text{Ca}_2\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2$	2900—2810	5
989	<i>Scapolite</i>	$(\text{Na,Ca})_4(\text{Al,Si})_{12}\text{O}_{24}(\text{CO}_3,\text{SO}_4,\text{Cl})$	2845—1930	2
990	<i>Glaucophane</i>	$\square\text{Na}_2(\text{Mg}_3\text{Al}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$	2845—1700	6
991	<i>Andradite</i>	$\text{Ca}_3\text{Fe}^{3+}_2\text{Si}_3\text{O}_{12}$	2742—2670	2
992	<i>Baddellyite</i>	ZrO_2	2742—2670	4
993	<i>Brucite</i>	$\text{Mg}(\text{OH})_2$	2742—2700	4
994	<i>Pumpellyite</i>	$\text{Ca}_2\text{Al}_3(\text{Si}_2\text{O}_7)(\text{SiO}_4)(\text{OH},\text{O})_2\cdot\text{H}_2\text{O}$	2680—2677	5
995	<i>Pyrope</i>	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	2710—2700	6
996	<i>Actinolite</i>	$\square\text{Ca}_2(\text{Mg,Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH},\text{F})_2$	2709—2701	--
997				
998	<i>Sapphirine</i>	$\text{Mg}_4(\text{Mg}_3\text{Al}_9)\text{O}_4(\text{Si}_3\text{Al}_9\text{O}_{36})$	2500—2448	1
999	<i>Rhodonite</i>	$\text{CaMn}_3\text{Mn}(\text{Si}_5\text{O}_{15})$	2500—2216	--
1000	<i>Osumilite</i>	$(\text{K,Na})(\text{Fe}^{2+},\text{Mg})_2(\text{Al,Fe}^{3+})_3(\text{Si,Al})_{12}\text{O}_{30}$	2485—496	1
1001	<i>Humite</i>	$\text{Mg}_9(\text{SiO}_4)_4(\text{F,OH})_2$	2070—1950	4
1002	<i>Periclase</i>	MgO	2058—2058	4
1003	<i>Coesite</i>	SiO_2	2050—2050	6
1004	<i>Jadeite</i>	$\text{NaAlSi}_2\text{O}_6$	2038—1270	6
1005	<i>Monticellite</i>	CaMgSiO_4	2000—1109	3
1006	<i>Spurrite</i>	$\text{Ca}_5(\text{SiO}_4)_2(\text{CO}_3)$	1750—248	3
1007				
1008	<i>Mullite</i>	$\text{Al}_{4+2x}\text{Si}_{2-2x}\text{O}_{10-x}$ ($x \approx 0.4$)	960—248	1
1009	<i>Merwinite</i>	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	794—684	3
1010	<i>Lawsonite</i>	$(\text{Ca,Sr})\text{Al}_2(\text{Si}_2\text{O}_7)(\text{OH})_2\cdot\text{H}_2\text{O}$	599—497	3
1011	<i>Bredigite</i>	$\text{Ca}_7\text{Mg}(\text{SiO}_4)_4$	354—248	--
1012	<i>Larnite</i>	Ca_2SiO_4	354—248	3
1013	<i>Rankinite</i>	$\text{Ca}_3\text{Si}_2\text{O}_7$	354—66	3
1014	<i>Tilleyite</i>	$\text{Ca}_5\text{Si}_2\text{O}_7(\text{CO}_3)_2$	300—300	3

- 1015
-
- 1016 1. The MED lists maximum and minimum ages for metamorphic occurrences. In many cases the
 1017 age range is large because a deposit is listed, for example, as “Precambrian.” Here we cite both
 1018 the greatest maximum and greatest minimum values. These two values may come from
 1019 different localities.
- 1020 2. Community as illustrated in Figure 1. Note that *actinolite*, *bredigite*, *spessartine*, *grunerite*,
 1021 *rhodonite*, and *piemontite* were not included in Figure 1 minerals.
- 1022 3. Diamond ages were provided by Shirey et al. (2013).
- 1023

1024 Earth’s first metamorphic rocks must have been thermally altered xenoliths and contact
 1025 zones (hornfels and sanidinite facies) associated with early Hadean igneous activity (> 4.5 Ga).
 1026 The appearance of new Hadean lithologies, including clay-rich sediments, arkosic sandstones,
 1027 and carbonates, provided additional protoliths for thermal metamorphism prior to 4.0 Ga.

1028 Indeed, the 8 oldest minerals in Table 4, all Paleoproterozoic or older (> 3.2 Ga), are associated
1029 with higher temperature metamorphic regimes.

1030 Also appearing in the Meso- and Neoproterozoic Eras (> 2.5 Ga) are representative minerals
1031 from regional and high-pressure metamorphic rocks (Table 4). The exposure of extensive
1032 regional metamorphic terranes by orogenesis and erosion, with lithologies corresponding to the
1033 Barrovian sequence of index mineral metamorphic zones, thus appears to have occurred
1034 significantly later in Earth history, perhaps in association with plate tectonics.

1035 More recently, rapid subduction and rebound of crustal wedges, coupled with a shallowing
1036 geothermal gradient, has produced distinctive suites of blueschist, eclogite, and ultrahigh
1037 pressure metamorphic suites. Some of these phases, including *glacophane*, *jadeite*, *pyrope*,
1038 *staurolite*, are first recorded in the Neoproterozoic or Paleoproterozoic Eras (2.8 to 2.0 Ga),
1039 perhaps signaling the commencement of subduction-driven tectonics. However, a number of
1040 key high-pressure metamorphic minerals, including *coesite*, *jadeite*, and *lawsonite*, are only
1041 known since 2.05 Ga (Table 4).

1042 The evolution of the metamorphic minerals continued into the Phanerozoic Eon (< 540 Ma).
1043 Intriguingly, 5 of the most recent (< 800 Ma) metamorphic minerals in Table 4—*bredigite*,
1044 *larnite*, *merwinite*, *rankinite*, and *tilleyite*—are all Ca-(Mg)-silicates that form by low-P contact
1045 metamorphism of limestone or dolomite. The lack of older known examples of these minerals
1046 may reflect a sparsity of dated examples, but enhanced biogenic production of carbonate
1047 lithologies may also have played a role. Indeed, the Phanerozoic Eon represents a distinctive
1048 phase in metamorphic mineral evolution. New biogenic lithologies such as coal, phosphorites,
1049 and reef carbonates were subjected to both regional and thermal metamorphism, while the

1050 intense burning of fossil hydrocarbons in the form of coal, oil, and natural gas created new
1051 pyrometamorphic regimes—processes to be considered in a subsequent contribution to this
1052 series. The evolution of metamorphic minerals thus epitomizes the kinds of changes in physical,
1053 chemical, and ultimately biological processes in the crust and upper mantle that exemplify
1054 mineral evolution over more than 4.5 billion years of Earth history.

1055

1056

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1065

1066

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1649 46–73.

1650 **Table 3. Summary of 94 frequently occurring metamorphic minerals, with their compositions,**
 1651 **abundances, and numbers of IMA species included in each mineral kind (see Supplementary Table 3).**
 1652

1653	Mineral Kind	Chemical Formula	Abundance¹	Community²	#IMA³
1654	Native Elements				
1655	<i>Diamond</i>	C	10	6	1
1656	<i>Graphite</i>	C	105	5	1
1657	Sulfides				
1658	<i>Chalcopyrite</i>	CuFeS ₂	99	2	1
1659	<i>Pyrite</i>	FeS ₂	120	--	1
1660	<i>Pyrrhotite</i>	Fe ₇ S ₈	192	--	1
1661	<i>Pentlandite</i>	(Ni,Fe) ₉ S ₈	21	5	1
1662	Oxides				
1663	<i>Rutile</i>	TiO ₂	297	--	1
1664	<i>Hematite</i>	Fe ₂ O ₃	24	--	1
1665	<i>Corundum</i>	Al ₂ O ₃	85	1	1
1666	<i>Periclase</i>	MgO	34	4	1
1667	<i>Baddeleyite</i>	ZrO ₂	18	4	1
1668	<i>Magnetite</i>	Fe ²⁺ Fe ³⁺ ₂ O ₄	429	--	1
1669	<i>Hercynite</i>	Fe ²⁺ Al ₂ O ₄	34	1	1
1670	<i>Spinel</i>	(Mg,Fe ²⁺)(Al,Fe ³⁺ ,Cr ³⁺) ₂ O ₄	263	4	1
1671	<i>Chromite</i>	Fe ²⁺ Cr ³⁺ ₂ O ₄	12	5	3
1672	<i>Ilmenite</i>	Fe ²⁺ Ti ⁴⁺ O ₃	181	--	1

1673	<i>Perovskite</i>	$\text{CaTi}^{4+}\text{O}_3$	12	3	1
1674	<i>Geikielite</i>	MgTiO_3	17	4	1
1675	<i>Pseudobrookite</i>	$\text{Fe}^{3+}_2\text{TiO}_5$	15	1	1
1676	Hydroxide				
1677	<i>Brucite</i>	$\text{Mg}(\text{OH})_2$	31	4	1
1678	Carbonates				
1679	<i>Calcite</i>	CaCO_3	645	4	1
1680	<i>Magnesite</i>	MgCO_3	16	5	1
1681	<i>Dolomite</i>	$\text{CaMg}(\text{CO}_3)_2$	152	4	2
1682	<i>Fe-Dolomite</i>	$\text{Ca}(\text{Mg,Fe})(\text{CO}_3)_2$ [0.15 < Fe/(Mg + Fe) < 0.50]	116	5	0
1683	<i>Aragonite</i>	CaCO_3	15	2	1
1684	<i>Spurrite</i>	$\text{Ca}_5(\text{SiO}_4)_2(\text{CO}_3)$	51	3	1
1685	<i>Tilleyite</i>	$\text{Ca}_5\text{Si}_2\text{O}_7(\text{CO}_3)_2$	16	3	1
1686	Phosphates				
1687	<i>Apatite</i>	$\text{Ca}_5(\text{PO}_4)_3(\text{F,OH,Cl})$	155	--	2
1688	Nesosilicates or Orthosilicates				
1689	<u><i>Olivine Group</i></u>				
1690	<i>Forsterite</i>	Mg_2SiO_4	173	4	1
1691	<i>Fayalite</i>	$\text{Fe}^{2+}_2\text{SiO}_4$	10	2	1
1692	<i>Olivine</i>	$(\text{Mg,Fe})_2\text{SiO}_4$ (0.3 < Fe/(Fe + Mg) < 0.7)	53	6	0
1693	<i>Monticellite</i>	CaMgSiO_4	77	3	1
1694	<u><i>Garnet Group</i></u>				
1695	<i>Almandine</i>	$\text{Fe}^{2+}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	367	--	1

1696	<i>Andradite</i>	$\text{Ca}_3\text{Fe}^{3+}_2\text{Si}_3\text{O}_{12}$	28	2	3
1697	<i>Grossular</i>	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	162	2	1
1698	<i>Pyrope</i>	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	192	6	2
1699	<u><i>Aluminosilicate Group</i></u>				
1700	<i>Andalusite</i>	Al_2SiO_5	146	1	1
1701	<i>Kyanite</i>	Al_2SiO_5	102	6	1
1702	<i>Sillimanite</i>	Al_2SiO_5	235	1	1
1703	<i>Mullite</i>	$\text{Al}_{4+2x}\text{Si}_{2-2x}\text{O}_{10-x}$ ($x \approx 0.4$)	62	1	1
1704	<u><i>Other Nesosilicates</i></u>				
1705	<i>Larnite</i>	Ca_2SiO_4	24	3	1
1706	<i>Merwinite</i>	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	38	3	1
1707	<i>Humite</i>	$\text{Mg}_9(\text{SiO}_4)_4(\text{F},\text{OH})_2$	21	4	2
1708	<i>Chloritoid</i>	$\text{Fe}^{2+}\text{Al}_2\text{O}(\text{SiO}_4)(\text{OH})_2$	46	6	3
1709	<i>Staurolite</i>	$\text{Fe}^{2+}_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$	52	1	1
1710	<i>Zircon</i>	ZrSiO_4	66	--	1
1711	<i>Titanite</i>	$\text{CaTi}^{4+}\text{SiO}_5$	186	--	1
1712	Sorosilicates or Disilicates				
1713	<i>Allanite</i>	$(\text{CaCe})(\text{AlAlFe}^{2+})\text{O}[\text{Si}_2\text{O}_7][\text{SiO}_4](\text{OH})$	16	5	5
1714	<i>Epidote</i>	$\text{Ca}_2(\text{Al}_2\text{Fe}^{3+})[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})$	157	--	4
1715	<i>Zoisite</i>	$\text{Ca}_2\text{Al}_3[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})$	156	6	1
1716	<i>Melilite</i>	$(\text{Ca},\text{Na})_2(\text{Mg},\text{Fe}^{2+},\text{Al},\text{Si})_3\text{O}_7$	108	3	3
1717	<i>Lawsonite</i>	$(\text{Ca},\text{Sr})\text{Al}_2(\text{Si}_2\text{O}_7)(\text{OH})_2\cdot\text{H}_2\text{O}$	11	6	2
1718	<i>Pumpellyite</i>	$\text{Ca}_2\text{Al}_3(\text{Si}_2\text{O}_7)(\text{SiO}_4)(\text{OH},\text{O})_2\cdot\text{H}_2\text{O}$	10	5	9

1719	<i>Rankinite</i>	$\text{Ca}_3\text{Si}_2\text{O}_7$	20	3	1
1720	<i>Vesuvianite</i>	$(\text{Ca,Na})_{19}(\text{Al,Mg,Fe})_{13}(\text{SiO}_4)_{10}(\text{Si}_2\text{O}_7)_4(\text{OH,F,O})_{10}$	15	2	10
1721	Cyclosilicates				
1722	<i>Tourmaline</i>	$(\square,\text{Na,Ca})(\text{Mg,Fe,Al})_3(\text{Mg,Al})_6(\text{Si}_6\text{O}_{18})(\text{BO}_3)_3(\text{OH,F})_3(\text{OH,O})$	47	5	18
1723	<i>Cordierite</i>	$(\text{Mg,Fe}^{2+})_2\text{Al}_4\text{Si}_5\text{O}_{18}$	395	1	2
1724	<i>Osumilite</i>	$(\text{K,Na})(\text{Fe}^{2+},\text{Mg})_2(\text{Al,Fe}^{3+})_3(\text{Si,Al})_{12}\text{O}_{30}$	13	1	4
1725	Inosilicates				
1726	<u><i>Pyroxene Group</i></u>				
1727	<i>Aegirine</i>	$(\text{Ca,Na})(\text{Fe}^{3+},\text{Mg,Fe}^{2+})\text{Si}_2\text{O}_6$	16	6	2
1728	<i>Augite</i>	$(\text{Ca,Mg,Fe}^{2+},\text{Fe}^{3+})_2(\text{Si,Al})_2\text{O}_6$ [0.15 < CaSiO ₃ < 0.45]	150	--	1
1729	<i>Diopside</i>	$\text{CaMgSi}_2\text{O}_6$	409	2	1
1730	<i>Hedenbergite</i>	$\text{CaFe}^{2+}\text{Si}_2\text{O}_6$	16	2	1
1731	<i>Jadeite</i>	$\text{NaAlSi}_2\text{O}_6$	34	6	1
1732	<i>Omphacite</i>	$(\text{Ca,Na})(\text{Mg,Fe,Al})\text{Si}_2\text{O}_6$	151	6	1
1733	<i>Orthopyroxene</i>	$(\text{Mg,Fe}^{2+})\text{SiO}_3$	281	--	2
1734	<u><i>Amphibole Group</i></u>				
1735	<i>Actinolite</i>	$\square\text{Ca}_2(\text{Mg,Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH,F})_2$	74	--	2
1736	<i>Anthophyllite</i>	$\square\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	52	1	6
1737	<i>Cummingtonite</i>	$\square\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	12	4	1
1738	<i>Glaucophane</i>	$\square\text{Na}_2(\text{Mg}_3\text{Al}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$	79	6	2
1739	<i>Hornblende</i>	$(\text{Na,K})\text{Ca}_2(\text{Mg,Fe}^{2+},\text{Al,Fe}^{3+})_5(\text{Si,Al})_8\text{O}_{22}(\text{OH,F,Cl})_2$	387	--	26
1740	<i>Richterite</i>	$\text{Na}(\text{CaNa})(\text{Mg,Fe}^{2+})_5(\text{Si,Al,Fe}^{3+})_8\text{O}_{22}(\text{OH})_2$	12	6	16
1741	<i>Tremolite</i>	$\square\text{Ca}_2(\text{Mg}_{5.0-4.5}\text{Fe}^{2+}_{0.0-0.5})\text{Si}_8\text{O}_{22}(\text{OH})_2$	122	4	2

1742	<u>Other Chain Silicates</u>				
1743	<i>Wollastonite</i>	CaSiO ₃	158	2	1
1744	<i>Sapphirine</i>	Mg ₄ (Mg ₃ Al ₉)O ₄ (Si ₃ Al ₉ O ₃₆)	28	1	2
1745	Phyllosilicates				
1746	<u>Mica Group</u>				
1747	<i>Biotite</i>	KFe ²⁺ ₂ (Fe ²⁺ ,Mg,Mn ²⁺)(Si,Al,Fe ³⁺) ₂ Si ₂ O ₁₀ (OH,F,Cl) ₂	822	--	6
1748	<i>Phlogopite</i>	[[KMg ₂ (Mg,Fe ²⁺ ,Mn ²⁺ ,Fe ³⁺ ,Ti ⁴⁺)(Si,Al,Fe ³⁺) ₂ Si ₂ O ₁₀ (OH,F) ₂]]	78	4	6
1749	<i>Muscovite</i>	K(Al,V,Fe ³⁺ ,Cr) ₂ (Si ₃ Al)O ₁₀ (OH) ₂	515	--	3
1750	<i>Phengite</i>	K(Al,Mg,Fe) ₂₋₃ (Si ₃ Al)O ₁₀ (OH) ₂	110	6	1
1751	<i>Paragonite</i>	NaAl ₂ (Si ₃ Al)O ₁₀ (OH) ₂	67	6	1
1752	<u>Other Layer Silicates</u>				
1753	<i>Chlorite</i>	(Mg,Fe ²⁺) ₅ (Al,Fe ³⁺)(Si ₃ AlO ₁₀)(OH) ₈	339	5	3
1754	<i>Serpentine</i>	(Mg,Fe) ₂ Al(AlSiO ₅)(OH) ₄	68	4	5
1755	<i>Talc</i>	Mg ₃ Si ₄ O ₁₀ (OH) ₂	73	5	1
1756	<i>Prehnite</i>	Ca ₂ Al(Si ₃ Al)O ₁₀ (OH) ₂	16	5	1
1757	Tectosilicate				
1758	<u>Silica Group</u>				
1759	<i>Quartz</i>	SiO ₂	1353	--	1
1760	<i>Tridymite</i>	SiO ₂	44	1	1
1761	<i>Coesite</i>	SiO ₂	23	6	1
1762	<i>Cristobalite</i>	SiO ₂	10	1	1
1763	<u>Feldspar Group</u>				
1764	<i>Albite</i>	NaAlSi ₃ O ₈	177	--	1

1765	<i>Anorthite</i>	$\text{CaAl}_2\text{Si}_2\text{O}_8$	78	2	1
1766	<i>Plagioclase</i>	$(\text{Na,Ca})\text{Al}(\text{Al,Si})_3\text{O}_8$	809	--	0
1767	<i>Kspar</i>	KAlSi_3O_8	411	--	1
1768	<i>Sanidine</i>	KAlSi_3O_8	102	1	1
1769	<u>Other Framework Silicates</u>				
1770	<i>Scapolite</i>	$(\text{Na,Ca})_4(\text{Al,Si})_{12}\text{O}_{24}(\text{CO}_3,\text{SO}_4,\text{Cl})$	33	2	3
1771	<i>Silicate Glass</i>	(Si,Al,Ca,Mg,Fe,O; $\text{SiO}_2 < 70$ wt %)	68	1	0

1772 ¹ Number of occurrences in a survey of the modes of 2785 metamorphic rocks; see Supplementary Table 3.

1773 ² The Community Number refers to the 6 communities illustrated in Figure 1A, based on a survey of 73 minerals.

1774 ³ The number of IMA-approved mineral species lumped into this mineral kind (see Supplementary Table 2). For example, *tourmaline* (which is not

1775 an IMA-approved mineral name) includes 18 IMA species. Note that *biotite*, *chlorite*, *Fe-dolomite*, *kspars*, *melilite*, *olivine*, *phengite*, *plagioclase*,

1776 *scapolite*, *serpentine*, and *silicate glass* are not IMA-approved names and do not correspond to any single IMA species.

1777

APPENDIX I. SYSTEMATIC MINERALOGY OF METAMORPHIC MINERALS

1778 Appendix I presents a systematic mineralogy of the 94 most frequently encountered
1779 metamorphic minerals. Supplementary Table 1 provides a list of 1220 metamorphic mineral
1780 species, the corresponding 755 metamorphic mineral kinds, and the distribution of these
1781 phases among 8 major groups of metamorphic rocks. This conversion of 1220 metamorphic
1782 minerals into 755 natural kinds requires several modifications to the IMA list, as detailed in
1783 Hazen et al (2022). In 568 instances, the IMA species name (e.g., augite) is identical to the
1784 natural kind name (*augite*). Note that in this contribution we *italicize* the names of mineral
1785 natural kinds to distinguish them from IMA-CNMNC-approved mineral species. In the case of
1786 652 IMA-approved species, we lump groups of two or more IMA species into single natural
1787 kinds. These numerous examples, resulting in a reduction from 652 species to 187 root natural
1788 kinds, are detailed in Supplementary Table 2 (see also Supplementary Read-Me File 2). For
1789 example, *pumpellyite* combines 9 IMA-approved species of the pumpellyite group. In 18
1790 instances, the name assigned to the natural kind is a group name that is not itself an approved
1791 IMA species name. Thus, *hornblende* lumps 26 IMA-approved species of calcic amphiboles,
1792 while *biotite* encompasses 6 species of Fe-bearing trioctahedral micas.

1793 We include five phases that do not correspond to an IMA-CNMNC-approved species in
1794 Supplementary Table 1. In the instance of *plagioclase*, we recognize intermediate compositions
1795 of the albite ($\text{NaAlSi}_3\text{O}_8$)—anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) solid solution with $0.15 < \text{Ca}/(\text{Ca} + \text{Na}) < 0.85$ as
1796 a separate natural kind. Similarly, *olivine* refers to intermediate compositions of the forsterite
1797 (Mg_2SiO_4)—fayalite (Fe_2SiO_4) solid solution for which $0.3 < \text{Fe}/(\text{Fe} + \text{Mg}) < 0.7$. *Fe-Dolomite*
1798 refers to intermediate compositions of the dolomite-ankerite solid solution, where $0.15 <$

1799 Fe/(Fe + Mg) < 0.50, many examples of which are incorrectly described as ankerite (Ferry et al.
1800 2015). *Phengite* is a fine-grained variety of muscovite $[K(Al,Mg,Fe)_{2-3}(AlSi_3)O_{10}(OH)_2]$, typically
1801 with excess Si, that is common in high-pressure metamorphic deposits. We also introduce
1802 *silicate glass*, an important amorphous phase in some pyrometamorphic lithologies, as a
1803 natural kind.

1804 Of the 755 mineral kinds recorded in Supplementary Tables 1 and 2, 94 phases are relatively
1805 common based on their occurrence in at least 10 rocks in 2785 metamorphic rocks (Table 3;
1806 Supplementary Table 3). Supplementary Table 3 also records a literature reference for each
1807 rock mode, the rock's locality, and information on the type of metamorphism, the metamorphic
1808 facies, and its protolith. Here we present brief descriptions of these 94 mineral kinds, arranged
1809 according to the New Dana Classification (Gaines et al. 1997).

1810 **Native Elements**

1811 Two polymorphs of carbon (C), *graphite* and *diamond*, with 105 and 10 occurrences in
1812 Supplementary Table 3, respectively, are the only native element minerals that occur in any
1813 significant abundance in metamorphic rocks, though more than two dozen rare native elements
1814 and metal alloys are listed in Supplementary Table 1. *Graphite* most frequently occurs in
1815 carbon-rich metapelites (Landis 1971; Diessel et al. 1978; Buseck and Huang 1985). However,
1816 *graphite* is also reported to occur as a product of retrograde metamorphism of *diamond*, at
1817 times as euhedral pseudomorphs (Pearson et al. 1989; Ferry 1992; Davies et al. 1993; Leech and
1818 Ernst 1998). In addition, Ross et al. (1991) reported an occurrence of *graphite* formed by the
1819 shearing of coal—an example of Phanerozoic metamorphism of a biotic protolith.

1820 Most *diamond* formation occurs in the mantle by precipitation from carbon-rich fluids (Jacob
1821 and Mikhail 2022; Kjarsgaard et al. 2022). However, in some instances, micrometer-scale
1822 *diamond* forms during subduction, ultra-deep metamorphism, and subsequent rebound of
1823 carbon-bearing crustal wedges (Dobrzhinetsky et al. 1995, 2022).

1824

1825 **Sulfides**

1826 More than 50 sulfide and other chalcogenide minerals have been reported from
1827 metamorphic rocks (Supplementary Table 1). However, only four iron-bearing sulfides, *pyrite*
1828 (FeS_2), *pyrrhotite* (Fe_7S_8), *chalcopyrite* (CuFeS_2), and *pentlandite* $[(\text{Ni,Fe})_9\text{S}_8]$, are relatively
1829 common. *Pyrrhotite* is the most commonly observed sulfide in our survey, occurring in 192
1830 metamorphic rocks. It frequently occurs with *graphite* in higher-grade regional metamorphic
1831 rocks (Hoscheck 1984; Ferry 1992), and it may form by solid-state transformation of *pyrite*
1832 coupled with sulfur loss (Bowles et al. 2011). It is also a common sulfide mineral associated with
1833 skarn deposits (Einaudi and Burt 1982).

1834 *Pyrite* (FeS_2) is the next most frequently reported metamorphic sulfide, with 120 occurrences
1835 in Supplementary Table 3. *Pyrite* is found in all metamorphic grades, including high-pressure
1836 regimes, and may form through solid-state transformation of *pyrrhotite* (Hall et al. 1987). *Pyrite*
1837 also occurs via contact metamorphism associated with skarn formation (Einaudi et al. 1981),
1838 and in shear zones (e.g., Harker 1950).

1839 *Chalcopyrite*, the only copper-bearing mineral among the most common metamorphic
1840 phases, is reported from 99 rocks in our survey. Most occurrences are as minor grains in
1841 regionally metamorphosed igneous and sedimentary lithologies (Ferry 1984, 1992, 1994; Ferry

1842 et al. 2001). It is likely that chalcopyrite, as an opaque and often micrometer-scale phase, is
1843 underrepresented in our study.

1844 The 21 occurrences of *pentlandite*, the only common nickel-bearing metamorphic minerals,
1845 are recorded exclusively from ultramafic lithologies (Ferry 1995; Ferry et al. 2005).

1846 In addition, it should be noted that *sphalerite* (ZnS) occurs in 9 of the rocks surveyed—a
1847 number that likely significantly underestimates the frequency of this opaque and typically
1848 minute zinc-bearing phase.

1849

1850 **Oxides**

1851 Oxide minerals occur in the entire range of metamorphic rocks. More than 50 species, most
1852 of them relatively rare, have been reported (Supplementary Table 1). We list 13 mineral kinds
1853 among the most frequently encountered metamorphic minerals.

1854 The simple oxide *rutile* (TiO₂) is reported in 297 of the metamorphic rocks from our study
1855 (Supplementary Table 3), most often in regional metamorphic rocks by transformation of prior
1856 Ti-bearing phases, including *titanite*, *ilmenite*, and titaniferous micas and *magnetite* (Bowles et
1857 al. 2011), but also in a range of pyrometamorphic (Grapes 2006), contact metamorphic
1858 (Reverdatto and S6bolev 1973), and shear zone (Harker 1950) rocks.

1859 Additionally, among the more common simple oxides is *corundum* (Al₂O₃; 85 occurrences),
1860 observed most frequently in silica-poor lithologies subjected to high temperature, notably in
1861 contact metamorphic zones. Al-rich lithologies with prominent *corundum*, often in association
1862 with *spinel*, *mullite*, *cordierite*, and/or *sanidine*, are known as “emery.” *Corundum* also occurs in

1863 pyrometamorphosed limestone xenoliths (Joplin 1968; Grapes 2006), as well as in high-grade
1864 regional metamorphic rocks (Harker 1950; Augustithus 1985).

1865 *Periclase* (MgO) is a common mineral in *calcite/dolomite* marbles, often in association with
1866 *brucite* (Carpenter 1967; Bowles et al. 2011). As early as 1940, Bowen described *periclase* as
1867 part of an evolutionary thermal metamorphic sequence (Bowen 1940). We record 36
1868 occurrences of *periclase*, primarily in limestone xenoliths and contact metamorphic
1869 environments (Augustithus 1985; Grapes 2006; Ferry and Rumble 2007).

1870 *Hematite* (Fe₂O₃), represented by 24 occurrences in our tabulation, forms from Fe-rich
1871 protoliths in oxidized environments. Contexts of metamorphic *hematite* include xenoliths,
1872 contact environments, iron formations, and regional metamorphism (Bowles et al. 2011).

1873 We record 18 occurrences of the zirconium oxide baddeleyite (ZrO₂) in both contact and
1874 regional metamorphic contexts (Ferry and Rumble 2007). That number that may
1875 underrepresent the frequency of baddeleyite because of its typical low modal abundance and
1876 small grain size.

1877 The most frequently encountered metamorphic oxides are members of the spinel group,
1878 which occur in 672 (24 %) of the 2785 metamorphic rocks we tabulated. With the general
1879 formula [(Mg,Fe²⁺)(Al,Fe³⁺,Cr³⁺,Ti)₂O₄], the spinel group encompasses a complex range of solid
1880 solutions (Bowles et al. 2011), of which four end-members are among the most commonly
1881 reported metamorphic minerals: *magnetite* (Fe²⁺Fe³⁺₂O₄), *spinel* (MgAl₂O₄; although “spinel”
1882 may also refer to the mineral group rather than the species in some modes), *chromite*
1883 (Fe²⁺Cr³⁺₂O₄), and *hercynite* (Fe²⁺Al₂O₄). In addition, several reports cite “pleonaste,” which

1884 refers to Fe²⁺-bearing intermediate compositions of the spinel-hercynite solid solution—
1885 examples that we include with *spinel*.

1886 *Magnetite* is by far the most frequently reported metamorphic oxide, occurring in 429 (15 %)
1887 of the 2785 metamorphic rocks we compiled, and in a wide range of metamorphic contexts
1888 (Joplin 1968; Reverdatto and S6bolev 1973; Grapes 2006). *Magnetite* often forms by thermal
1889 alteration of ferric iron oxide/hydroxides, as well as through the introduction of Fe-rich fluids—
1890 a situation in which the distinction between metamorphism and metasomatism may be
1891 blurred.

1892 The Mg-Al oxide *spinel*, with 263 occurrences in our list, is found in numerous contact and
1893 regional metamorphic contexts, principally as a high-temperature mineral in metacarbonates
1894 and Al-rich protoliths (Harker 1950; Botha 1983; Carswell 1990; Grapes 2006).

1895 *Hercynite*, which forms in high-grade metamorphic environments, often in association with
1896 *corundum*, *mullite*, and/or *sillimanite*, is represented by 34 examples in Supplementary Table 3.
1897 Metamorphic contexts include xenolith, contact, and regional environments (Harker 1950;
1898 Grapes 2006; Bowles et al. 2011).

1899 We list 12 occurrences of metamorphic *chromite*—a number that likely underestimates this
1900 most common chromium mineral because it is opaque and easily mistaken for other Fe-bearing
1901 oxides. *Chromite* is most often associated with ultramafic lithologies, particularly ophiolites.

1902 Four titanium-bearing double oxides are listed among the 94 most common metamorphic
1903 phases. We record *Ilmenite* (FeTiO₃) from 181 xenoliths, contact metamorphic rocks, or regional
1904 metamorphic formations, notably forming via alteration of mafic and Fe-bearing lithologies
1905 (Reverdatto and S6bolev 1973; Carswell 1990; Grapes 2006). *Geikielite* (MgTiO₃), the

1906 magnesium analog of ilmenite, occurs in 17 contact and regional metasedimentary rocks in
1907 Supplementary Table 3. Geikeilite protoliths include carbonates, calc silicates, pelites, and
1908 sandstones. *Perovskite* (CaTiO_3) is reported from 12 rocks, primarily in xenoliths and contact
1909 metamorphic environments with impure limestone (Murdoch 1951; Fulignati et al. 2000;
1910 Grapes 2006). *Pseudobrookite* ($\text{Fe}^{3+}_2\text{TiO}_5$), which we record in 15 primarily xenolith and contact
1911 metamorphic rocks, forms most often by the high-temperature oxidation of *ilmenite* (Agrell and
1912 Langley 1958; Smith 1969; Basta and Shaalan 1974).

1913 *Brucite* [$\text{Mg}(\text{OH})_2$], the only relatively common hydroxide mineral in metamorphic rocks,
1914 occurred in 31 rocks of our survey. It is typically the consequence of hydration of *periclase* in
1915 altered Ca-Mg carbonates (Nakajima et al. 1992; Ferry et al. 2002; Ferry and Rumble 2007;
1916 Bowles et al. 2011).

1917

1918 **Carbonates**

1919 At least 70 carbonate minerals have been reported from metamorphic rocks (Supplementary
1920 Table 1), though only seven species occur with any significant frequency. By far the most
1921 abundant carbonates are *calcite* (CaCO_3), *dolomite* [$\text{CaMg}(\text{CO}_3)_2$], and the intermediate
1922 composition *Fe-dolomite* [*dolomite* with a significant *ankerite* $\text{CaFe}(\text{CO}_3)_2$ component], with
1923 645, 152, and 116 occurrences in our compilation, respectively. *Calcite* and *dolomite* most often
1924 occur in metamorphosed limestones and other carbonate-bearing protoliths (Harker 1950;
1925 Reverdatto and S6bolev 1973; Chang et al. 1996; Grapes 2006). In many instances, these phases
1926 form through recrystallization of prior carbonates to form a marble (Chang et al. 1996; Philpotts
1927 and Ague 2009). *Fe-dolomite* (often reported as “ankerite” in the petrologic literature) is found

1928 primarily in regionally metamorphosed sediments (Ferry 1992, 1994, 2007; Ferry et al. 2015)
1929 where it formed through carbonation reactions during metamorphism/metasomatism (Spooner
1930 and Fyfe 1973).

1931 Metamorphic *magnesite* (MgCO_3) with 16 occurrences is characteristic of altered ophiolites,
1932 where it occurs in association with talc and serpentine. It typically forms via the carbonation of
1933 Mg-bearing oxides and silicates (Chang et al. 1996).

1934 *Aragonite*, a high-pressure form of CaCO_3 , was recorded in 15 rocks of eclogite, blueschist,
1935 and ultrahigh-pressure facies carbonate rocks (Carswell 1990; Carswell and Compagnoni 2003;
1936 Philpotts and Ague 2009).

1937 Two silicate carbonates, *spurrite* [$\text{Ca}_5(\text{SiO}_4)_2(\text{CO}_3)$] with 51 examples and *tilleyite*
1938 [$\text{Ca}_5\text{Si}_2\text{O}_7(\text{CO}_3)_2$] with 16 examples, arise when *calcite* and *wollastonite* react at high
1939 temperature (Tuttle and Harker 1957; Zharikov and Shmulovich 1969).

1940

1941 **Phosphates**

1942 Of the more than 50 metamorphic phosphates recorded in Supplementary Table 1, only the
1943 calcium phosphate *apatite* [$\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{OH})$] is widely reported, with 155 occurrences in
1944 Supplementary Table 3. We lump two common species, fluorapatite and hydroxylapatite, which
1945 are rarely differentiated in reports of metamorphic mineral modes. The majority of these
1946 *apatite* occurrences are in high-grade metamorphosed mafic igneous rocks, including granulites
1947 and eclogites (Harker 1950; Joplin 1968; Carswell 1990). In addition, *apatite* has been reported
1948 from contact metamorphic and shear environments (Harker 1950; Joplin 1968).

1949

1950 **Silicates**

1951 Silicates constitute the majority of metamorphic minerals, both volumetrically and in terms
1952 of diversity. In Supplementary Tables 1 and 2 we record 746 silicate mineral species,
1953 corresponding to 418 root natural kinds, of which 66 are frequently encountered metamorphic
1954 phases. In the following sections we review these more common silicates.

1955

1956 **Nesosilicates or Orthosilicates**

1957 Orthosilicates, with silicon exclusively in insular SiO_4^{4-} structural groups, are characteristic
1958 minerals in environments with relatively low Si, notably those associated with carbonate, calc-
1959 silicate, or aluminous protoliths (Deer et al. 1982). We detail 21 orthosilicates in addition to the
1960 orthosilicate-carbonate mineral *spurrite*, described above. Of these 22 phases, 16 contain
1961 essential Ca and/or Al.

1962 *Olivine Group*: We recognize four members of the olivine group $[(\text{Mg,Fe,Ca})_2\text{SiO}_4]$ as
1963 important metamorphic minerals (Deer et al. 1982). The Mg olivine *forsterite* (ideally Mg_2SiO_4)
1964 is reported in 173 of the rocks we surveyed, notably via contact, regional, or high-pressure
1965 metamorphism of silica-poor ultramafic (Springer 1974; Pinsent and Hirst 1977) or carbonate-
1966 bearing (Weeks 1956; Schreyer et al. 1972; Suzuki 1977) protoliths. We also distinguish *olivine*
1967 as intermediate Mg-Fe compositions with $0.3 < \text{Fe}/(\text{Fe} + \text{Mg}) < 0.7$, which are common in
1968 metamorphosed mafic and ultramafic rocks (53 occurrences; Reverdatto and S6bolev 1973;
1969 Ferry et al. 1987).

1970 *Fayalite* (ideally Fe_2SiO_4) is much less common, occurring in 10 rocks with Fe-rich protoliths,
1971 including mafic rocks and iron formations (Joplin 1968; Simmons et al. 1974; Floran and Papike

1972 1978; Carswell 1990). Note that metamorphic Fe-dominant olivines with intermediate
1973 compositions are less common than examples close to either end-member (Deer et al. 1982).

1974 *Monticellite* (CaMgSiO_4), with 77 occurrences, is commonly found in contact metamorphic
1975 environments with siliceous carbonate lithologies, often forming with increasing temperature
1976 at the expense of *diopside*, *forsterite*, and/or *wollastonite* (Bowen 1940; Turner 1967; Deer et
1977 al. 1982). *Monticellite* frequently co-occurs with *forsterite*, as the solid solution between these
1978 two olivine group minerals is limited (Warner and Luth 1973).

1979 *Garnet Group*: The garnet group is represented by four relatively common metamorphic
1980 phases, occurring in 745 (27 %) of 2785 rocks in our survey. Garnets collectively display a
1981 significant compositional range, typically with solid solutions among two or three end-members
1982 (Deer et al. 1982; Chiama et al. 2020, 2022). Ideal end-members of these minerals are
1983 *almandine* [$\text{Fe}^{2+}_3\text{Al}_2(\text{SiO}_4)_3$], *andradite* [$\text{Ca}_3\text{Fe}^{3+}_2(\text{SiO}_4)_3$], *grossular* [$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$], and *pyrope*
1984 [$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$], often with a significant *spessartine* [$\text{Mn}^{2+}_3\text{Al}_2(\text{SiO}_4)_3$] component, as well,
1985 though true Mn-dominant *spessartine* is recorded in only 9 occurrences in our compilation
1986 (Woodland 1938; Roy 1965; Jan and Symmes 1977).

1987 In some instances, such as *pyrope-almandine-spessartine* (“pyralspite”) from eclogites and
1988 other high-grade metamorphic rocks, *grossular-andradite* (“grandite”) from the contact
1989 metamorphism of carbonate-bearing sediments, and contact metamorphic garnets in the
1990 *grossular-spessartine-almandine* field (Shimazaki 1977), the compositional ranges among end-
1991 members may be continuous, thus warranting lumping of species into a single metamorphic
1992 mineral kind. However, until cluster analysis (Gregory et al. 2019; Boujibar et al. 2021; Hystad et

1993 al. 2021) can be performed on a wide range of garnet compositions from known paragenetic
1994 environments, we will treat these five types of metamorphic garnet separately.

1995 *Almandine*, with 367 occurrences in Supplementary Table 3, is the commonest garnet in
1996 metamorphic rocks (Harker 1950; Joplin 1968; Reverdatto and S6bolev 1973; Botha 1983;
1997 Augustithus 1985). Most *almandine* forms in a regional metamorphic context, derived from
1998 mafic or pelitic protoliths (Atherton 1964; Deer et al. 1982), including high-pressure examples
1999 from blueschist (Coleman and Lee 1963; Banno and Matsui 1965), eclogite (Coleman et al.
2000 1965), and granulite (Buddington 1952; Eskola 1952) facies. In addition, *almandine* from
2001 contact metamorphism of pelites is not uncommon (Tilley 1926; Stewart 1942), while it also
2002 occurs in some metamorphosed iron formations (Klein 1966).

2003 *Pyrope's* 192 entries are overwhelmingly from high-pressure metamorphic environments, in
2004 many instances from eclogite-grade rocks with mafic precursors, most commonly in
2005 association with *omphacite* (Carswell 1990). Metamorphic *pyrope* typically has a significant
2006 *almandine* component (Deer et al. 1982).

2007 The great majority of 162 *grossular* occurrences in Supplementary Table 3 arise from contact
2008 metamorphism of calcareous rocks, often in association with *diopside* and/or *wollastonite*
2009 (Watters 1958; Reverdatto and S6bolev 1973), or in regional metamorphic formations, also
2010 with carbonate-bearing protoliths (Tilley 1927; Sylvester and Anderson 1976). In addition, 28
2011 occurrences of the Ca-Fe³⁺ garnet *andradite* arise predominantly from contact and regional
2012 metamorphism of calc-silicate rocks (Harker 1950; White 1959; Shedlock and Essene 1979). In
2013 several instances, contact metamorphic garnets have so-called "grandite" compositions
2014 intermediate between *grossular* and *andradite* (Coombs et al. 1977; Tulloch 1979).

2015 Three additional Ca-Mg orthosilicates, *bredigite* [Ca₇Mg(SiO₄)₄] with 6 occurrences (Tilley
2016 and Vincent 1948; Grapes 2006), *larnite* (Ca₂SiO₄) with 24 occurrences (Deer et al. 1986), and
2017 *merwinite* [Ca₃Mg(SiO₄)₂] with 38 occurrences (Larsen and Foshag 1921; Reverdatto and
2018 Sóbolev 1973), are frequently found in contact metamorphosed calc-silicate protoliths, often in
2019 association with the calc-silicates *melilite*, *rankinite*, and *spurrite* (Joplin 1968; Deer et al. 1986;
2020 Grapes 2006). *Merwinite* is also reported as an ultrahigh pressure mantle phase (Zedgenizov et
2021 al. 2014).

2022 We lump three compositionally similar IMA species—humite, clinohumite, and
2023 hydroxylclinohumite—into *humite* [Mg₇₋₉(SiO₄)₄(F,OH)₂]. Members of the humite group differ in
2024 the ratios of two structural modules, one of forsterite composition [Mg₂(SiO₄)] and the other of
2025 brucite composition [Mg(OH,F)₂]. Reports of metamorphic mineral modes seldom distinguish
2026 between humite [Mg₉(SiO₄)₄(OH,F)₂] and clinohumite [Mg₇(SiO₄)₄(OH,F)₂], nor between the OH-
2027 and F-dominant species. We record 21 occurrences of *humite*, all of which are characteristic of
2028 the contact metamorphism of dolomite-bearing sediments (Tilley 1951; Joplin 1968; Deer et al.
2029 1982). Note that two other members of the humite group (Van Valkenburg 1961), *norbergite*
2030 [Mg₃(SiO₄)₄(OH,F)₂] and *chondrodite* [Mg₅(SiO₄)₄(OH,F)₂], are also contact metamorphic
2031 minerals, but did not appear as common phases in our tabulations of metamorphic rock modes.

2032 Three aluminosilicate (Al₂SiO₅) polymorphs, *andalusite*, *kyanite*, and *sillimanite*, are
2033 abundant constituents of many metapelites, with 146, 102, and 235 occurrences in
2034 Supplementary Table 3, respectively. These phases, which can coexist at their invariant triple
2035 point (approximately 500 °C and 0.4 GPa; Hodges and Spear 1982; Bohlen et al. 1991; Pattison
2036 2001), have received special attention for their ability to document the pressure-temperature

2037 regimes of their host rocks (Barrow 1893; Zen 1969; Deer et al. 1982; Whitney 2002; Philpotts
2038 and Ague 2009). *Sillimanite*, the high-temperature, low-pressure polymorph, is a common
2039 phase in a variety of metapelites subjected to hornblende hornfels, granulite, and
2040 pyrometamorphic (sanidinite) conditions (Reverdatto and S6bolev 1973; Botha 1983; Grapes
2041 2006). *Mullite* [$\text{Al}_{4+2x}\text{Si}_{2-2x}\text{O}_{10-x}$ ($x \approx 0.4$)] is also a high-temperature, low-pressure orthosilicate
2042 that we record from 62 pyrometamorphic rocks, often in association with *sillimanite* (Grapes
2043 2006).

2044 *Andalusite* forms in pelitic protoliths at low pressure and moderate temperature (< 770 °C),
2045 notably from albite-epidote hornfels and hornblende hornfels facies (Read 1923; Guitard 1965;
2046 Reverdatto and S6bolev 1973). *Kyanite*, the highest-pressure crustal polymorph of Al_2SiO_5 , is
2047 frequently encountered in regional and high-pressure metamorphic rocks with aluminous
2048 precursors (Carswell 1990; Carswell and Compagnoni 2003). The aluminosilicates may record
2049 either prograde or retrograde metamorphism. For example, Lal (1969) described *andalusite* and
2050 *kyanite* formed via retrograde metamorphism from cordierite-bearing rocks, and Gates and
2051 Speer (2022) record retrograde *kyanite* after *sillimanite* in metapelite shear zones.

2052 *Chloritoid* [$(\text{Fe}^{2+}, \text{Mg}, \text{Mn}^{2+})\text{Al}_2\text{O}(\text{SiO}_4)(\text{OH})_2$], with 46 occurrences in our tabulation, is most
2053 commonly formed by regional or high-pressure metamorphism of pelitic rocks (Joplin 1968;
2054 Carswell 1990). We lump three IMA-CNMNC-approved species, chloritoid [$\text{Fe}^{2+}\text{Al}_2\text{O}(\text{SiO}_4)(\text{OH})_2$],
2055 magnesiochloritoid [$\text{MgAl}_2\text{O}(\text{SiO}_4)(\text{OH})_2$], and ottrelite [$\text{Mn}^{2+}\text{Al}_2\text{O}(\text{SiO}_4)(\text{OH})_2$], because they
2056 form a continuous solid solution and they are rarely differentiated in reports of metamorphic
2057 rock modes. The broad pressure-temperature stability field of *chloritoid* leads to a wide range

2058 of assemblages, from low-grade, clay-mineral- and *phengite*-bearing facies to high-grade rocks
2059 with *kyanite*, *pyrope-almandine*, and/or *staurolite* (Halferdahl 1961).

2060 *Staurolite* [(Fe²⁺,Mg)₂Al₉Si₄O₂₃(OH)] is another common phase derived by regional or high-
2061 pressure metamorphism of pelitic sediments. Its 52 occurrences in Supplementary Table 3
2062 reflect a range of *P-T* conditions of formation, from low-grade assemblages with *chloritoid* and
2063 *quartz*, medium-grade assemblages with *almandine* and *kyanite*, and high-grade assemblages
2064 with *sillimanite* and *plagioclase* (Deer et al. 1982; Augustithus 1985; Carswell 1990). *Staurolite*
2065 is also observed in the contact metamorphism of pelites (Reverdatto and S6bolev 1973; Grapes
2066 2006).

2067 *Titanite* (CaTiSiO₅; commonly reported as “sphene”) occurs as a minor phase in 186
2068 metamorphic rocks in our survey in a variety of contexts (Harker 1950; Joplin 1968; Reverdatto
2069 and S6bolev 1973; Carswell 1990). *Zircon* (ZrSiO₄), another volumetrically minor phase, is listed
2070 in 66 of 2785 rocks in our tabulation, including a wide range of contact and regional
2071 metamorphic lithologies (Joplin 1968; Carswell 1990; Grapes 2006). *Titanite* and *zircon* are
2072 particularly durable accessory minerals that are widespread in igneous and sedimentary
2073 formations; therefore, their occurrence in metamorphic rocks sometimes derives from protolith
2074 minerals that have been little altered.

2075 Though not among the more common metamorphic orthosilicates, *willemite* (Zn₂SiO₄) is an
2076 important mineral in some metamorphosed Pb-Zn deposits, such as the sillimanite-grade
2077 deposits at Franklin, New Jersey (Pinger 1950; Frondel 1990). In this case, which may be
2078 relevant to minerals in many metamorphic environments, *willemite* occurs both as a major
2079 phase in the ore and as a secondary phase in thin hydrothermal veins. These two generations of

2080 *willemite*, furthermore, have distinct properties: both forms are fluorescent, but only the
2081 secondary *willemite* has persistent luminescence as a consequence of its greater arsenic
2082 content (Rakovan and Waychunas 1996). With their distinct modes of formation and attributes,
2083 these coexisting forms of willemite represent two different mineral kinds in our evolutionary
2084 system.

2085

2086 **Sorosilicates or Disilicates**

2087 Sorosilicates incorporate the double-tetrahedron pyrosilicate group ($\text{Si}_2\text{O}_7^{6-}$). We find eight
2088 sorosilicate root natural kinds, corresponding to at least 35 IMA-CNMNC-approved species,
2089 among the 94 most frequently encountered metamorphic mineral kinds. All of these phases, in
2090 addition to the disilicate-carbonate mineral *tilleyite* described earlier, are calcium-bearing
2091 minerals that occur most frequently in the contact metamorphic zones of limestone and
2092 dolomite.

2093 The most common metamorphic sorosilicates are from the diverse epidote group (Deer et al.
2094 1986; Armbruster et al. 2006). We lump 4 monoclinic species (including Fe^{3+} -bearing
2095 clinozoisite) into *epidote* $[\text{Ca}_2(\text{Al}_2\text{Fe}^{3+})[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})]$ with 149 occurrences; 5 rare-earth
2096 element-bearing epidote group minerals into *allanite* $[(\text{CaCe})(\text{AlAlFe}^{2+})\text{O}[\text{Si}_2\text{O}_7][\text{SiO}_4](\text{OH})]$ with
2097 16 occurrences (though certainly under-reported); and orthorhombic *zoisite*
2098 $[\text{Ca}_2\text{Al}_3[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})]$ with 156 occurrences. In addition, Mn-bearing *piemontite*
2099 $[\text{Ca}_2\text{Al}_2\text{Mn}^{3+}(\text{Si}_2\text{O}_7)(\text{SiO}_4)\text{O}(\text{OH})]$ is an important phase in metamorphosed manganese deposits,
2100 though we record only 7 occurrences. Metamorphic *epidote* is found most commonly via
2101 contact metamorphism of carbonate-bearing sediments and mafic igneous rocks (Joplin 1968;

2102 Reverdatto and S6bolev 1973), but also in regional (Harker 1950), high-pressure (Carswell
2103 1990), and xenolith (Grapes 2006) contexts. Note, however, that it may be difficult to
2104 distinguish metamorphic *epidote* and *zoisite* (see below) from examples formed by
2105 metasomatism (Joplin 1968).

2106 *Zoisite* generally forms at lower metamorphic grades than *epidote*, though it can coexist with
2107 *epidote* in medium-grade regional metamorphic rocks derived from calcareous sediments or
2108 mafic igneous rocks (Myer 1966; Ackermann and Rasse 1973; Raith 1976). *Zoisite* is also
2109 common in *kyanite*-bearing eclogite (Carswell and Compagnoni 2003), where it may form by a
2110 prograde reaction from *lawsonite* (Deer et al. 1986).

2111 We lump two species, lawsonite and itoigawaite, into the root kind *lawsonite*
2112 $[(Ca,Sr)Al_2(Si_2O_7)(OH)_2 \cdot H_2O]$, with 11 occurrences in Supplementary Table 3. *Lawsonite* forms
2113 exclusively in high-pressure blueschist or eclogite facies rocks (Philpotts and Ague 2009),
2114 commonly in association with *glaucophanes* and an epidote group mineral, either *zoisite* or
2115 *epidote* (Coleman et al. 1965; Carswell 1990).

2116 *Rankinite* ($Ca_3Si_2O_7$), with 20 occurrences, is found exclusively in contact metamorphic rocks,
2117 commonly in association with *larnite*, *melilite*, *spurrite*, and/or *wollastonite* (Reverdatto and
2118 S6bolev 1973; Grapes 2006).

2119 The melilite group includes the solid solution between 6kermanite $[Ca_2(Al_2SiO_7)]$ and
2120 gehlenite $[Ca_2(MgSi_2O_7)]$, as well as alumo6kermanite $[(Ca,Na)_2(Al,Mg,Fe^{2+})(Si_2O_7)]$ —minerals
2121 that we lump into the root mineral kind *melilite*. With 108 occurrences in Supplementary Table
2122 3, *melilite* is a common mineral in pyrometamorphosed siliceous limestone and dolomite,

2123 particularly at pyroxene hornfels and sanidinite facies (Reverdatto and S6bolev 1973; Grapes
2124 2006), often forming at the expense of *diopside* or *anorthite* (Bowen 1940; Reverdatto 1970).

2125 *Pumpellyite* $[\text{Ca}_2(\text{Al}, \text{Fe}^{2+}, \text{Fe}^{3+})_3(\text{Si}_2\text{O}_7)(\text{SiO}_4)(\text{OH}, \text{O})_2 \cdot \text{H}_2\text{O}]$ lumps 9 closely-related species of
2126 Ca-Al-Fe sorosilicates that are found most frequently in the low-grade zeolite and pumpellyite-
2127 prehnite facies of regional metamorphism. We list 10 occurrences, all of which occur in low-
2128 grade metapelites (Joplin 1968; Botha 1983; Augustithus 1985). However, Deer et al. (1986)
2129 note that Al-rich *pumpellyite* also occurs in blueschist facies, and Fe- and Mn-rich pumpellyite
2130 may occur in mineralized skarn zones.

2131 We lump 10 IMA-CNMNC-approved species, most of which are rare compositional variants,
2132 into *vesuvianite* $[(\text{Ca}, \text{Na})_{19}(\text{Al}, \text{Mg}, \text{Fe})_{13}(\text{SiO}_4)_{10}(\text{Si}_2\text{O}_7)_4(\text{OH}, \text{F}, \text{O})_{10}]$. We record 15 occurrences in
2133 contact metamorphosed limestone, in which it is a characteristic skarn mineral, commonly in
2134 association with *diopside*, *grossular*, and/or *wollastonite* (Harker 1950). *Vesuvianite* occurs less
2135 commonly in regional metamorphosed limestones (Tilley 1927; Deer et al. 1982). Note that, as
2136 with the example of *epidote*, it may be difficult to distinguish *vesuvianite* formed by
2137 metamorphism versus metasomatism (Joplin 1968).

2138

2139 **Cyclosilicates**

2140 Members of the cordierite, tourmaline, and osulmilite groups are relatively common
2141 metamorphic cyclosilicates. We lump the species cordierite (with Mg) and sekaninaite (with
2142 Fe^{2+}) into the root mineral kind *cordierite* $[(\text{Mg}, \text{Fe}^{2+})_2\text{Al}_4\text{Si}_5\text{O}_{18}]$, which, with 395 occurrences in
2143 Supplementary Table 3, is among the most common minerals in contact and regionally
2144 metamorphosed pelites (Joplin 1968; Reverdatto and S6bolev 1973; Botha 1983; Grapes 2006).

2145 Deer et al. (1986) detail a wide range of *cordierite* parageneses, including pyrometamorphosed
2146 xenoliths, contact metamorphosed argillaceous sediments, and a range of regional
2147 metamorphic facies, including low-pressure, high-temperature assemblages with *andalusite*;
2148 moderate-pressure assemblages with *sillimanite* and garnet; and high-pressure assemblages
2149 with *kyanite*.

2150 *Tourmaline* [(Na,Ca,□)(Mg,Al,Fe²⁺,Fe³⁺,Ti⁴⁺)₃(Al,Fe³⁺,Mg)₆(Si₆O₁₈)(BO₃)₃(OH)₃(O,F)] is the only
2151 common boron-bearing mineral in metamorphic rocks (Deer et al. 1986; Henry et al. 2011;
2152 Henry and Dutrow 2012). We lump 18 IMA-CNMNC-approved species of the tourmaline group
2153 (Supplementary Table 1), all of which have been reported from regional metamorphic
2154 environments. The 47 *tourmaline* occurrences listed in Supplementary Table 3, including
2155 several examples of *tourmaline*-dominant tourmalinites, are from metapelites (Harker 1950;
2156 Joplin 1968). Joplin (1968) suggests that metamorphic tourmaline occurs in 3 distinct ways: as a
2157 remnant mineral of the protolith, through metamorphism of a borate-containing lithology, or as
2158 the result of boron metasomatism.

2159 *Osumilite* [(K,Na)(Fe²⁺,Mg)₂(Al,Fe³⁺)₃(Si,Al)₁₂O₃₀] was reported in 13 of our mineral modes,
2160 typically from ultrahigh temperature metamorphosed pelites, in which it commonly occurs
2161 with *cordierite*, *orthopyroxene*, *sanidine*, and/or *sillimanite* (Harley 2021).

2162

2163 **Inosilicates**

2164 Among the 94 relatively common metamorphic minerals listed in Table 2, 16 are chain
2165 silicates, including several members of the pyroxene (7 kinds) and amphibole (7 kinds) groups

2166 (Deer et al. 1997a, 1997b). Inosilicates are one of the most common classes of metamorphic
2167 minerals, occurring in 1387 (50 %) of the 2785 metamorphic rocks in Supplementary Table 3.

2168

2169 Pyroxene Group: We consider 7 root kinds of pyroxene group single-chain silicates, most of
2170 which lie in or near the [(Ca,Mg,Fe)₂Si₂O₆] quadrilateral (Deer et al. 1997a).

2171 *Orthopyroxene* lumps 281 occurrences of orthorhombic pyroxenes, most often described as
2172 enstatite (the Mg end-member) or “hypersthene” (with Mg ~ Fe²⁺) but sometimes “bronzite”
2173 (with Mg > Fe²⁺) or ferrosilite (the Fe²⁺ end-member), always lying close to the MgSiO₃—
2174 Fe²⁺SiO₃ binary. *Orthopyroxene* most often occurs in granulite, eclogite, and UHT facies of
2175 metamorphosed ultramafic and mafic igneous rocks, in which it is often the most abundant
2176 mafic phase (Joplin 1968; Augustithus 1985; Carswell and Compagnoni 2003). It also occurs in
2177 lower-grade regional metamorphic rocks (Joplin 1968; Botha 1983), with iron-rich examples in
2178 metamorphosed iron formations (Kranck 1961; Simmons et al. 1974). *Orthopyroxene* is not
2179 uncommon in contact metamorphic environments, including pyrometamorphosed xenoliths
2180 (Reverdatto and Söbolev 1973; Grapes 2006). In some instances, Mg-rich *orthopyroxene* is
2181 associated with carbonate minerals (Schreyer et al. 1972; Ohnmacht 1974).

2182 Three Ca-bearing clinopyroxenes, *diopside* [Ca(Mg,Fe²⁺)Si₂O₆; 409 occurrences in
2183 Supplementary Table 3), *hedenbergite* (CaFe²⁺Si₂O₆; 16 occurrences), and the ternary solid
2184 solution *augite* [(Ca,Mg,Fe²⁺)₂Si₂O₆, typically with 0.5 < Ca/(Mg+Fe) < 0.9; 150 occurrences], are
2185 common in a wide variety of metamorphic rocks (Deer et al. 1997a). Pyroxenes close to the
2186 continuous CaMg—CaFe²⁺ solid solution between *diopside* and *hedenbergite* are most typical of
2187 thermally metamorphosed carbonate and calc-silicate rocks, occurring in xenolithes and

2188 contact metamorphic contexts (Grapes 2006). We define *diopside* broadly to include most
2189 intermediate Mg-Fe compositions (e.g., “salite” and “ferrosalite”), as well as Al-bearing
2190 “fassaite.” More than 80% of occurrences of *diopside*, the most abundant pyroxene in our
2191 survey, arise from contact metamorphism. Diopside also occurs in regional and high-pressure
2192 metamorphic rocks, with several examples from amphibolite facies (Harker 1950; Augustithus
2193 1985) and eclogite facies (Carswell 1990; Carswell and Compagnoni 2003).

2194 *Hedenbergite* displays much the same parageneses as *diopside*, but with Fe-rich protoliths
2195 (Joplin 1968; Augustithus 1985). We debated whether to lump these two end-members, but
2196 *hedenbergite* appears to form a discrete cluster of metamorphic clinopyroxenes with low Mg.
2197 Cluster analysis of igneous and metamorphic clinopyroxenes represents an important future
2198 research goal.

2199 The IMA-CNMNC-approved species augite, including clinopyroxenes in the
2200 $[(\text{Ca}, \text{Mg}, \text{Fe}^{2+})_2\text{Si}_2\text{O}_6]$ system with Ca occupying between ~25 and ~45 atom percent of the Ca-
2201 Mg-Fe sites, is equivalent to our root kind *augite*. The 150 occurrences in Supplementary Table
2202 3, while mostly from contact metamorphism or pyrometamorphism of ultramafic/mafic
2203 lithologies (Reverdatto and S6bolev 1973; Grapes 2006), also include representatives derived
2204 by regional metamorphism of mafic and intermediate igneous protoliths (Harker 1950; Joplin
2205 1968; Ferry 1987).

2206 Three Na-bearing clinopyroxenes, *Aegirine* $[(\text{Ca}, \text{Na})(\text{Fe}^{3+}, \text{Mg}, \text{Fe}^{2+})\text{Si}_2\text{O}_6]$; 16 occurrences],
2207 *jadeite* $(\text{NaAlSi}_2\text{O}_6)$; 34 occurrences), and *omphacite* $[(\text{Ca}, \text{Na})(\text{Mg}, \text{Fe}, \text{Al})\text{Si}_2\text{O}_6]$; 151 occurrences]
2208 are especially characteristic of high-pressure metamorphic environments. *Aegirine*, in which we
2209 lump two IMA-CNMNC-approved species aegirine $(\text{NaFe}^{3+}\text{Si}_2\text{O}_6)$ and aegirine-augite

2210 [(Ca,Na)(Fe³⁺,Mg,Fe²⁺)Si₂O₆], is the least common of these phases in metamorphic rocks, being
2211 found primarily in the context of mafic and intermediate igneous rocks subjected to ultrahigh
2212 pressure and eclogite facies (Carswell 1990), though *aegirine* also occurs via contact
2213 metamorphism of alkaline rocks (Reverdatto and S6bolev 1973). A complication is the
2214 formation of *aegirine* through sodium metasomatism of prior pyroxenes (Moore 1973; Deer et
2215 al. 1997a).

2216 *Jadeite* is a diagnostic phase found exclusively in high-pressure metamorphic environments,
2217 including blueschist facies, eclogite facies, and ultrahigh pressure metamorphic rocks (Carswell
2218 1990). It often forms through the iconic reaction *albite* → *jadeite* + *quartz* (Deer et al. 1997a,
2219 and references therein). *Jadeite* commonly incorporates up to 15 mol % of an
2220 *aegirine/omphacite* component; however, a significant compositional gap separates *jadeite*
2221 from these phases, which often coexist in high-pressure assemblages (Coleman and Clark 1968).

2222 *Omphacite*, which represents a solid solution among *aegirine*, *diopside*, and *jadeite*, is a
2223 relatively common phase in high-pressure metamorphic rocks. All 151 occurrences in our
2224 tabulation were reported from blueschist, eclogite, or ultrahigh-pressure environments, most
2225 often with ultramafic or mafic protoliths and often in association with *glaucophane*,
2226 *pyrope/almandine*, and *quartz/coesite* (Carswell 1990; Carswell and Compagnoni 2003).

2227

2228 Pyroxenoid Group: Two members of the inosilicate pyroxenoid group, *wollastonite* (CaSiO₃;
2229 158 occurrences) and the Mn-bearing *rhodonite* [CaMn₃Mn(Si₅O₁₅); 8 occurrences, not listed
2230 among the top 94 phases], are most commonly associated with skarn zones. Almost all

2231 *wollastonite* reports are from carbonate or calc-silicate protoliths subjected to pyroxene
2232 hornfels or sanidinite facies metamorphism (Reverdatto and S6bolev 1973; Grapes 2006).

2233 *Rhodonite*, which lumps 4 closely-related species of Mn pyroxenoids, is most frequently
2234 encountered in the high-pressure metamorphic environments of Mn-rich protoliths (Carswell
2235 1990), notably by reaction of *rhodochrosite* (MnCO_3 ; Hori 1962), though it can also form
2236 through Mn metasomatism (Bilgrami 1956).

2237

2238 *Amphibole Group*: The amphibole group of double-chain silicates, which boasts more than
2239 110 IMA-CNMNC-approved species (<https://rruff.info/ima>; accessed January 13, 2023), is likely
2240 the most diverse of all mineral structure types (Deer et al 1997b; Hawthorne et al. 2011). Here,
2241 we provisionally lump 55 amphibole species known to occur in metamorphic rocks into 7 root
2242 mineral kinds. It should be noted, however, that the variety of amphibole parageneses, coupled
2243 with the extensive and complex solid solutions and miscibility gaps among many species, render
2244 any suggestion of amphibole mineral kinds tentative, at best. In the context of metamorphism,
2245 we have yet to determine if different facies, different protoliths, effects of metasomatism,
2246 prograde versus retrograde formation, and other factors may yield numerous distinct
2247 combinations of paragenesis and attributes. We require data resources with analyses of tens of
2248 thousands of well-characterized amphibole specimens, coupled with advanced methods of
2249 cluster analysis (Boujibar et al. 2021; Hystad et al. 2021). Such an epic endeavor could represent
2250 a lifetime of fruitful study for an ambitious young mineralogist.

2251 *Anthophyllite* [$\square(\text{Mg}, \text{Fe}^{2+})_2(\text{Mg}, \text{Fe}^{2+}, \text{Fe}^{3+}, \text{Al})_5(\text{Si}, \text{Al})_8\text{O}_{22}(\text{OH})_2$; with 52 occurrences in
2252 Supplementary Table 3], lumps 6 species of the complex anthophyllite/ferro-

2253 anthophyllite/gedrite/ferro-gedrite solid solution of orthorhombic amphiboles (Ferré 1989). An
2254 unresolved question regards the possible presence of a miscibility gap in this system between
2255 Al-rich (at times with Na) and Al-poor orthoamphiboles (Hawthorne et al. 1980; Spear 1982). If
2256 so, then at least two root mineral kinds would be warranted. Most of the examples in our
2257 compilation arise from hornblende-hornfels or pyroxene-hornfels facies contact metamorphism
2258 of ultramafic/mafic igneous rocks or pelitic sediments, often in association with *biotite*,
2259 *cordierite*, and *quartz* (Reverdatto and S6bolev 1973). We also record a number of instances of
2260 *anthophyllite* in regional metamorphic settings, including amphibolite and granulite facies
2261 metamorphism of pelites and ultramafic rocks (Joplin 1968).

2262 The closely-related clinopyroxenes *cummingtonite* [$\square\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$; with 12
2263 occurrences] and *grunerite* [$\square\text{Fe}^{2+}_2\text{Fe}^{2+}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$; with 8 occurrences, hence not listed among
2264 the top 94] are the monoclinic polymorphs of anthophyllite and ferro-anthophyllite. All but one
2265 of the *cummingtonite* examples in our tabulation, with Mg/(Mg+Fe) generally > 0.4 (i.e., in
2266 some instances with Fe > Mg), are from metapelites subjected to hornblende-hornfels facies
2267 contact metamorphism (Reverdatto and S6bolev 1973). The more iron-rich *grunerite* examples,
2268 by contrast, are primarily from amphibolite or granulite facies regionally metamorphosed iron
2269 formations (Joplin 1968; Kimball and Spear 1984). Therefore, we provisionally distinguish these
2270 two closely-related mineral kinds based on paragenetic mode, even though they may display
2271 continuous solid solution between the Mg and Fe^{2+} end-members. It should be noted that as a
2272 result of miscibility gaps, *cummingtonite* and *grunerite* often occur in assemblages with
2273 multiple amphiboles, including calcic *hornblende*, Al-bearing *anthophyllite*, and/or a sodic
2274 amphibole (Deer et al. 1997b).

2275 Several calcic clinoamphiboles are common constituents of metamorphic rocks. *Tremolite*
2276 $[\square\text{Ca}_2(\text{Mg}_{5.0-4.5}\text{Fe}^{2+}_{0.0-0.5})\text{Si}_8\text{O}_{22}(\text{OH},\text{F})_2$; with 122 occurrences] is typically an almost pure Ca-Mg
2277 phase (i.e., low Fe^{2+}) formed from ultramafic/mafic igneous or calc-silicate sediments in
2278 contact, regional, and high-pressure metamorphic environments. Most of the examples in
2279 Supplementary Table 3 are from muscovite-hornfels, hornblende-hornfels, or pyroxene-
2280 hornfels contact metamorphic zones, in which *tremolite* is associated with *diopside*, *dolomite*,
2281 *grossular*, *talc*, and/or other Ca-Mg phases (Reverdatto and S6bolev 1973). We lump the OH^- -
2282 and F^- -bearing species, which display a complete solid solution and share the same paragenesis.

2283 *Actinolite* $[\square\text{Ca}_2(\text{Mg},\text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH},\text{F})_2$; with 74 occurrences] lumps the species actinolite
2284 and ferro-actinolite, spanning a range $0.9 > \text{Mg}/(\text{Mg} + \text{Fe}^{2+}) > 0$ (Deer et al. 1997b). Though
2285 chemically and structurally similar to *tremolite*, *actinolite* is distinguished both by its greater
2286 Fe^{2+} content and by its common association in metapelites or metabasites with *biotite*, *epidote*
2287 or *zoisite*, and/or *quartz* in high-pressure, regional, or contact metamorphic settings (Harker
2288 1950; Joplin 1968; Botha 1983; Carswell 1990).

2289 We lump 26 IMA-CNMNC-approved metamorphic species of Ca-(+/-Na,K)-clinoamphiboles
2290 into *hornblende* $[(\text{Na},\text{K})\text{Ca}_2(\text{Mg},\text{Fe}^{2+},\text{Al},\text{Fe}^{3+})_5(\text{Si},\text{Al})_8\text{O}_{22}(\text{OH},\text{F},\text{Cl})_2$; with 387 occurrences]. This
2291 complex group displays significant compositional plasticity, with solid solutions among Na, K,
2292 and vacancies in alkali sites; Mg- Fe^{2+} - Fe^{3+} -Al in octahedral sites; and Al- Fe^{3+} -Si in tetrahedral
2293 sites, as well as among OH, F, and Cl (Deer et al. 1997b; Hawthorne et al. 2011; see
2294 Supplementary Tables 1 and 2). *Hornblende*, a defining phase in hornblende-hornfels and
2295 amphibolite facies rocks, appears in numerous metamorphic environments, including contact
2296 metamorphism (albite-epidote to sanidinite facies; Reverdatto and S6bolev 1973; Grapes

2297 2006), regional metamorphism (greenschist to granulite facies; Harker 1950; Joplin 1968), and
2298 high-pressure metamorphism (blueschist to eclogite facies; Reverdatto and S6bolev 1973;
2299 Carswell 1990). *Hornblende* protoliths, similarly, span a wide range of igneous, sedimentary,
2300 and metamorphic rocks. *Hornblende* in metamorphic rocks commonly coexists with other
2301 amphiboles, including *anthophyllite*, *cummingtonite*, and *grunerite* (Deer et al. 1997b). Given
2302 the complexity of this mineral group, cluster analyses of numerous hornblende samples based
2303 on composition, paragenesis, and mineral associations, would doubtless reveal many distinct
2304 kinds of *hornblende*.

2305 We lump a wide range of Na-Ca clin amphiboles into *richterite*, defined here as
2306 $[(\square, \text{Na})(\text{NaCa})(\text{Mg}, \text{Fe}^{2+}, \text{Al}, \text{Fe}^{3+})_5(\text{Si}, \text{Al}, \text{Fe}^{3+})_8\text{O}_{22}(\text{OH})_2]$. Although we record only 12 occurrences
2307 in Supplementary Table 3, most of which were originally described as barroisite [nominally
2308 $(\square\text{NaCa})(\text{Mg}_3\text{Al}_2)(\text{Si}_7\text{Al})\text{O}_{22}(\text{OH})_2]$ or winchite $[(\square\text{NaCa})(\text{Mg}_4\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2]$, we lump 16 IMA-
2309 CNMNC-approved species into the root natural kind *richterite*, while acknowledging that much
2310 more work is needed to fully characterize these minerals and their associated parageneses.
2311 Most of the *richterite* occurrences that we record are metamorphosed mafic rocks from
2312 eclogite facies, almost always in association with *omphacite*, *pyrope*, and *rutile* (Binns 1967;
2313 Carswell 1990), though it is reported from regionally metamorphosed basalt, as well (Iwasaki
2314 1960).

2315 The sodium amphibole *glaucophane* $[\square\text{Na}_2(\text{Mg}, \text{Fe}^{2+})_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2]$; with 79 occurrences]
2316 lumps 2 species, glaucophane and ferro-glaucophane, which form a Mg-Fe²⁺ solid solution. All
2317 of the examples in Supplementary Table 3 are from high-pressure metamorphism (most

2318 commonly blueschist or eclogite facies, but also ultrahigh-pressure facies) of
2319 mafic/intermediate igneous rocks or Mg-bearing sediments (Augustithus 1985; Carswell 1990).

2320 One additional inosilicate group, *sapphirine* [(Mg,Fe²⁺,Al,Fe³⁺)₈O₂(Al,Si)₆O₁₈, 28 occurrences],
2321 is important as a key indicator of the temperature (> 900 °C) of ultrahigh temperature
2322 metamorphic rocks formed from ultramafic protoliths (Monchoux 1972; Deer et al. 1997a;
2323 Carswell and Compagnoni 2003; Harley 2021). It commonly occurs in association with
2324 *orthopyroxene* and *sillimanite*.

2325

2326 **Phyllosilicates**

2327 *Mica Group*: With 1244 occurrences in Supplementary Table 3 (45% of the 2795 rocks
2328 surveyed), the mica minerals are prominent constituents of many metamorphic lithologies
2329 (Guidotti 1984; Fleet 2003). We lump 15 IMA-CNMNC-approved species into five root mineral
2330 kinds of micas: *biotite*, *phlogopite*, *phengite*, *muscovite*, and *paragonite*. However, there
2331 undoubtedly exist many more kinds of metamorphic micas, the identification of which will
2332 require the construction of extensive mica databases and application of cluster analysis (Hazen
2333 2019). In particular, widely occurring metamorphic *biotite* and *muscovite* will likely be split into
2334 multiple natural kinds.

2335 We define the familiar group of dark-colored, Fe²⁺-bearing trioctahedral mica species as
2336 *biotite* [KFe²⁺₂(Fe²⁺,Mg,Mn²⁺)(Si,Al,Fe³⁺)₂Si₂O₁₀(OH,F,Cl)₂; 822 occurrences]. We lump 6 IMA-
2337 CNMNC-approved species, which are themselves rarely identified in the petrographic literature.
2338 Few minerals occur in as a diverse array of metamorphic environments as *biotite*, which we
2339 record from low-pressure pyrometamorphic, contact, regional, and high-pressure

2340 metamorphism, typically of pelites, but also of ultramafic, mafic, intermediate, acidic, and
2341 (rarely) agpaitic igneous rocks, as well as Fe-bearing impure carbonate and calc-silicate
2342 protoliths (Harker 1950; Joplin 1968; Reverdatto and S6bolev 1973; Botha 1983; Carswell 1990;
2343 Fleet 2003; Grapes 2006).

2344 We also lump 6 Mg-dominant species of trioctahedral micas, which are generally lighter in
2345 color than *biotite*, as *phlogopite* [$\text{KMg}_2(\text{Mg}, \text{Fe}^{2+}, \text{Mn}^{2+}, \text{Fe}^{3+}, \text{Ti}^{4+})(\text{Si}, \text{Al}, \text{Fe}^{3+})_2\text{Si}_2\text{O}_{10}(\text{OH}, \text{F})_2$; with 78
2346 occurrences]. Though often combined with *biotite* in some descriptions of mica (e.g., Fleet
2347 2003), and consequently sometimes reported as *biotite* in the petrologic literature, *phlogopite*
2348 displays distinct mineral associations in metamorphosed high-Mg, low-Fe environments,
2349 including ultramafic and dolomitic carbonate protoliths (Joplin 1968; Reverdatto and S6bolev
2350 1973). Owing to their diverse parageneses and compositional range, trioctahedral micas
2351 represent yet another mineral group that is ripe for investigation by cluster analysis.

2352 The dioctahedral aluminous mica *muscovite* [$\text{K}(\text{Al}, \text{Fe}^{3+}, \text{Cr})_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2$; 515 occurrences],
2353 commonly reported with the varietal names illite, phengite, or sericite, is most characteristic of
2354 regionally and contact metamorphosed pelites (Reverdatto and S6bolev 1973; Philpotts and
2355 Ague 2009), which represent most of the occurrences recorded in Supplementary Table 3.
2356 *Muscovite*, among the first phases to form during diagenesis of clay minerals (Fleet 2003), also
2357 occurs in a wide range of other contexts, including contact and regional metamorphosed
2358 arkosic, calc-silicate, and impure carbonate sediments (Philpotts and Ague 2009), as well as a
2359 variety of igneous protoliths (Harker 1950; Carswell 1990).

2360 We also include the fine-grained, Si-rich white mica *phengite* (110 occurrences) as a separate
2361 kind, even though it falls under IMA's definition of muscovite. Phengite is most commonly
2362 associated with high-pressure metamorphism (Carswell 1990).

2363 The sodium trioctahedral mica *paragonite* [$\text{NaAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2$; 67 occurrences] is
2364 characteristic of high-pressure eclogite facies metamorphism of mafic igneous rocks, often in
2365 association with *glaucophanes*, *kyanite*, *omphacite*, and/or *pyrope* (Carswell 1990). *Paragonite*,
2366 often intimately intermixed with *phengite* (with which it has limited solid solution; e.g.,
2367 Thompson and Thompson 1976; Guidotti et al. 1994), also occurs in low- and medium-grade
2368 metapelites, in which it can form by both prograde and retrograde reactions (Chatterjee 1970;
2369 Guidotti 1984; Guidotti and Sassi 1998; Fleet 2003). *Paragonite* also frequently co-occurs with
2370 the so-called "brittle mica" *margarite* [$\text{CaAl}_2(\text{Si}_2\text{Al}_2)\text{O}_{10}(\text{OH})_2$] in a wide range of metamorphic
2371 grades of metasediments (Guidotti 1984; Fleet 2003); however, *margarite* is relatively rare in
2372 comparison to the micas described above, being reported from only one of the metamorphic
2373 rocks in our survey (Carswell and Compagnoni 2003, their Table 2).

2374

2375 Other phyllosilicates: More than 30 other IMA-CNMNC-approved layer silicates occur in
2376 metamorphic rocks (Supplementary Table 1). Most of these minerals (e.g., apophyllite group,
2377 *gillespite*, *pyrophyllite*, *stilpnomelane*, *zussmanite*) occur only rarely in metamorphic rocks. Note
2378 that we do not list diagenetically-formed clay minerals as metamorphic phases (Wilson 2013);
2379 they will be considered further in Part IX of this series. However, *chlorite*, *prehnite*, *serpentine*,
2380 and *talc* are included in our list of 94 relatively common metamorphic phases (Deer et al. 2009).

2381 *Chlorite* [(Mg,Fe²⁺)₅(Al,Fe³⁺)(Si₃AlO₁₀)(OH)₈; 339 occurrences] encompasses 3 IMA-CNMNC-
2382 approved species of Mg-Fe²⁺-Al-(Fe³⁺) layer silicates: chamosite, clinochlore, and sudoite.
2383 *Chlorite* is common in pelites subjected to greenschist and amphibolite facies metamorphism
2384 (Harker 1950; Joplin 1968; Botha 1983), as well as from muscovite-, hornblende-, and pyroxene-
2385 hornfels facies contact metamorphism of pelites and basic igneous rocks (Joplin 1968;
2386 Reverdatto and S6bolev 1973), often in association with *albite*, *biotite*, *muscovite*, and/or
2387 *quartz*. In addition, Coleman et al. (1965) and Carswell (1990) record more than a dozen
2388 examples of *chlorite* in eclogite facies high-pressure metamorphism. *Chlorite* forms through a
2389 variety of pathways, including prograde and retrograde metamorphism, both with and without
2390 external aqueous fluids. As such, *chlorite* represents a mineral whose often uncertain
2391 parageneses grade continuously from regional or “burial” metamorphism to metasomatism to
2392 hydrothermal alteration (Deer et al. 2009).

2393 We lump 5 IMA-CNMNC-approved species, including three structural variants of
2394 Mg₃Si₂O₅(OH)₄ (antigorite, chrysotile, and lizardite), aluminous amesite, and Fe-bearing
2395 greenalite, into *serpentine* [(Mg,Fe²⁺,Al,Fe³⁺)₃(Al,Si)Si(OH)₄; 68 occurrences]. Most examples in
2396 Supplementary Table 3 are from low- to moderate-grade regional metamorphism of
2397 ultramafic/mafic igneous or pelitic protoliths (Joplin 1968; Philpotts and Ague 2009), in which
2398 they form primarily by retrograde/hydrothermal reactions from olivine and Mg-rich pyroxene
2399 or by prograde metamorphism of serpentinite (Deer et al. 2009, and references therein). Given
2400 its varied modes of formation, coupled with multiple polymorphs, cluster analysis of
2401 metamorphic *serpentine* is warranted.

2402 *Talc* [$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$; 73 occurrences] is characteristic of Mg-rich protoliths over a wide
2403 range of pressure-temperature condition. Examples include thermal metamorphism of
2404 *dolomite*-bearing sediments (Tilley 1948; Reverdatto and S6bolev 1973; Augustithus 1985),
2405 high-pressure (blueschist and eclogite facies) metamorphism of basic igneous rocks (Chopin
2406 1981; Carswell 1990), and greenschist to amphibolite grade regional metamorphism of
2407 ultramafic rocks (Harker 1950; Joplin 1968). Of special note are high-pressure to ultrahigh
2408 pressure (> 0.6 GPa) *talc-kyanite-(quartz/coesite)* assemblages known as “whiteschists”
2409 (Schreyer 1977), which form in the Mg-Al-Si-H (“MASH”) system, at times with $\text{P}_{\text{H}_2\text{O}}$
2410 approximately equal to the total pressure.

2411 *Prehnite* [$\text{Ca}_2\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2$; 16 occurrences], though most familiar as a hydrothermal
2412 phase associated with zeolites in amygdaloidal basalt, is also common in the eponymous
2413 prehnite-pumpellyite facies of low-grade regional metamorphism (Coombs 1960; Philpotts and
2414 Ague 2009). *Prehnite*, often in association with *chlorite* and *quartz*, is also present occasionally
2415 in metamorphosed basic igneous and pelitic sedimentary rocks from zeolite to lower
2416 amphibolite grades (Harker 1950; Joplin 1968; Botha 1983), at times the result of retrograde
2417 reactions (Coombs 1993).

2418

2419 **Tectosilicates**

2420 A wide range of framework silicates, including the silica group, feldspars, feldspathoids, and
2421 zeolites (Deer et al. 2001, 2004), occur in metamorphic rocks, with one or more examples
2422 reported in 1595 (67 %) of the 2785 rocks surveyed in Supplementary Table 3. We focus
2423 attention on 10 mineral kinds that occur most frequently.

2424

2425 Silica Group: Four silica group minerals—*quartz*, high-pressure *coesite*, and high-
2426 temperature *crystalite* and *tridymite*—span the entire range of metamorphic environments,
2427 occurring in all but the most Si-deficient rocks (Deer et al. 2004).

2428 *Quartz* (SiO₂), with 1353 occurrences in our study (49 % of rocks in Supplementary Table 3),
2429 is the most common metamorphic mineral. It occurs in pyrometamorphosed xenoliths, contact
2430 metamorphic rocks, metamorphosed iron-manganese formations, high-pressure and regional
2431 metamorphic settings, metasomatized rocks, and shear zones (Supplementary Table 3 and
2432 references therein), often by recrystallization of protolith *quartz* (Deer et al. 2004). *Quartz* is
2433 stable in all crust and upper mantle pressure-temperature regimes except above ~2.7 GPa,
2434 where it transforms to *coesite*, or at low pressure above ~850 °C, where *crystalite* and
2435 *tridymite* are the stable silica phases.

2436 *Coesite* (SiO₂; 23 occurrences) is restricted to ultrahigh pressure (> 2.7 GPa) metamorphic
2437 environments, where it is typically associated with *kyanite*, *omphacite*, and/or *pyrope* (Carswell
2438 and Compagnoni 2003). Several reports describe *coesite* as inclusions in upper mantle phases,
2439 including *pyrope* (Chopin 1984; Schertl et al. 1991) and *diamond* (Stachel et al. 2022, and
2440 references therein).

2441 *Crystalite* (10 occurrences) and *tridymite* (44 occurrences) are high-temperature, low-
2442 pressure polymorphs of SiO₂ that occur almost exclusively in sedimentary rocks that have been
2443 thermally metamorphosed (pyroxene hornfels or sandinite facies) by basic igneous rocks (Agrell
2444 and Langley 1958; Reverdatto and S6bolev 1973; Black 1989; Grapes 2006). These two minerals
2445 co-occur in 7 of the 10 reported rocks with *crystalite*. *Tridymite* and *crystalite* also are

2446 associated in some burning coal deposits with temperatures that may exceed 1100 °C (Bustin
2447 and Matthews 1982; Grapes 2006), and therefore are the consequence of Phanerozoic
2448 biological precursors (to be considered in Part XII).

2449

2450 Feldspar Group: Metamorphic feldspar group minerals display compositions close to two
2451 binary solid solutions (Deer et al. 2001): the Na-Ca plagioclase feldspars and the Na-K alkali
2452 feldspars. In both instances we suggest modifications of the nomenclature approved by the
2453 IMA-CNMNC.

2454 In the case of the plagioclase series [(CaAl,NaSi)AlSi₂O₈], we identify *albite* as compositions
2455 close to NaAlSi₃O₈ [Na/(Na+Ca) > 0.85 and often with > 10 mol % KAlSi₃O₈], *anorthite* as close to
2456 CaAl₂Si₂O₈ [Ca/(Ca+Na) > 0.85], and *plagioclase* as having intermediate compositions between
2457 ~An₂₀ and ~An₇₀ as valid root mineral kinds. We justify this division based on the existence of
2458 the so-called peristerite and Huttenlocker miscibility gaps between ~An₂₋₁₇ and An₆₅₋₈₈,
2459 respectively. As a consequence, several authors have recorded coexisting *albite-plagioclase* and
2460 *plagioclase-anorthite* pairs (Evans 1964; Botha 1983).

2461 *Albite*, with 177 occurrences in Supplementary Table 3, is observed in a wide range of
2462 thermal, regional, and high-pressure metamorphic environments, with both igneous and
2463 sedimentary protoliths (Harker 1950; Joplin 1968; Reverdatto and Söbolev 1973; Philpotts and
2464 Ague 2009). *Anorthite* (78 occurrences) is more restricted in its occurrences, being found
2465 primarily as a contact metamorphic mineral derived from calc-silicate and carbonate-bearing
2466 sediments (Grapes 2006), though it is also found in regionally metamorphosed mafic and calc-
2467 silicate rocks from amphibolite to granulite facies (Joplin 1968). *Plagioclase* (809 occurrences),

2468 like *quartz*, *albite*, and *kspar* (see below) is not a particularly diagnostic phase in metamorphic
2469 rocks because it occurs across the full spectrum of thermal, regional, and high-pressure
2470 metamorphic environments, with an equally broad range of igneous, sedimentary, and
2471 metamorphic protoliths. For a given protolith, the anorthite content of plagioclase tends to
2472 increase with metamorphic grade (Deer et al. 2001). Note that most reports of “plagioclase” in
2473 the older metamorphic literature lack compositional information; thus, some of these
2474 occurrences may fit our definitions of *albite* or *anorthite*.

2475 The alkali feldspars are complicated by the existence of three K-rich (KAlSi₃O₈) variants—the
2476 higher-temperature (> 500 °C) monoclinic *sanidine* and two lower-temperature triclinic phases,
2477 microcline and orthoclase, which are often reported as “kspar” in the literature of metamorphic
2478 petrology. An additional consideration is that alkali feldspars of intermediate compositions
2479 often exsolve Na- and K-rich phases, typically reported as “perthite.” In our study, we adopt
2480 the name *kspar* for microcline and orthoclase, and record both *albite* and *kspar* for perthite.

2481 *Sanidine* (102 occurrences) is most commonly found in thermally metamorphosed rocks of
2482 pyroxene hornfels or sanidinite grade (Grapes 2006), though it also has been reported from
2483 ultrahigh pressure metamorphism of pelites (Carswell 1990; Carswell and Compagnoni 2003)
2484 and ultrahigh temperature regimes (Harley 2021).

2485 *Kspar* (411 occurrences) has been reported from thermal (zeolite to pyroxene hornfels
2486 facies), regional (amphibolite to granulite facies), and high-pressure (eclogite to ultrahigh
2487 pressure facies) metamorphic environments. Protoliths for *kspar* include mafic, acidic, and
2488 agpaitic igneous rocks and arkosic, pelitic, and carbonate-bearing sedimentary rocks (Harker
2489 1950; Joplin 1968; Reverdatto and Söbolev 1973; Carswell 1990; Deer et al. 2001).

2490 At the temperatures of UHT metamorphism (> 900 °C), an additional complication is the
2491 occurrence of Ca-Na-K ternary feldspars, which typically exsolve to a perthite with coexisting
2492 plagioclase and alkali feldspar lamellae (Harley 2008; Harley 2021, their Figure 20).

2493

2494 Scapolite Group: Three species of the scapolite group are lumped as *scapolite*
2495 $[(\text{Na,Ca})_4\text{Al}_3(\text{Al,Si})_3\text{Si}_6\text{O}_{24}(\text{CO}_3,\text{SO}_4,\text{Cl})$, with 33 occurrences]. *Scapolite* is not infrequently
2496 observed in medium- to high-grade contact (hornblende-hornfels and pyroxene hornfels facies)
2497 and regional (amphibolite and granulite facies) metamorphosed pelites and calc-silicate
2498 sediments (Joplin 1968; Reverdatto and Sobolev 1973), and has also been reported from the
2499 albite-epidote hornfels facies contact metamorphism of amygdaloidal basalt (Joplin 1968).

2500

2501 Zeolite Group: The zeolite facies is the lowest pressure-temperature regime of
2502 metamorphism, with temperatures < 200 °C at pressures < 0.3 GPa (Philpotts and Ague 2009).
2503 Most zeolite minerals form via low-temperature aqueous processes, including fluid interactions
2504 with cooling basalt and authigenesis (Deer et al. 2004). Nevertheless, some zeolite occurrences
2505 are attributed to metamorphism, *sensu stricto*. Though not sufficiently abundant to include
2506 among the most common metamorphic phases, *analcime* (2 occurrences), *laumontite* (1), and
2507 *wairakite* (2), as well as 6 undifferentiated reports of “zeolite,” were listed in modes of low-
2508 grade metamorphosed mafic igneous rocks and pelites (Joplin 1968).

2509

2510 Feldspathoid Group: None of the members of the sub-silicic feldspathoid framework silicate
2511 group is common in metamorphic rocks. Nevertheless, *kalsilite*, *leucite*, and *nepheline* (with 5,

2512 2, and 4 occurrences, respectively) are representative of undersaturated pyrometamorphosed
2513 calc-silicates (Grapes 2006).

2514

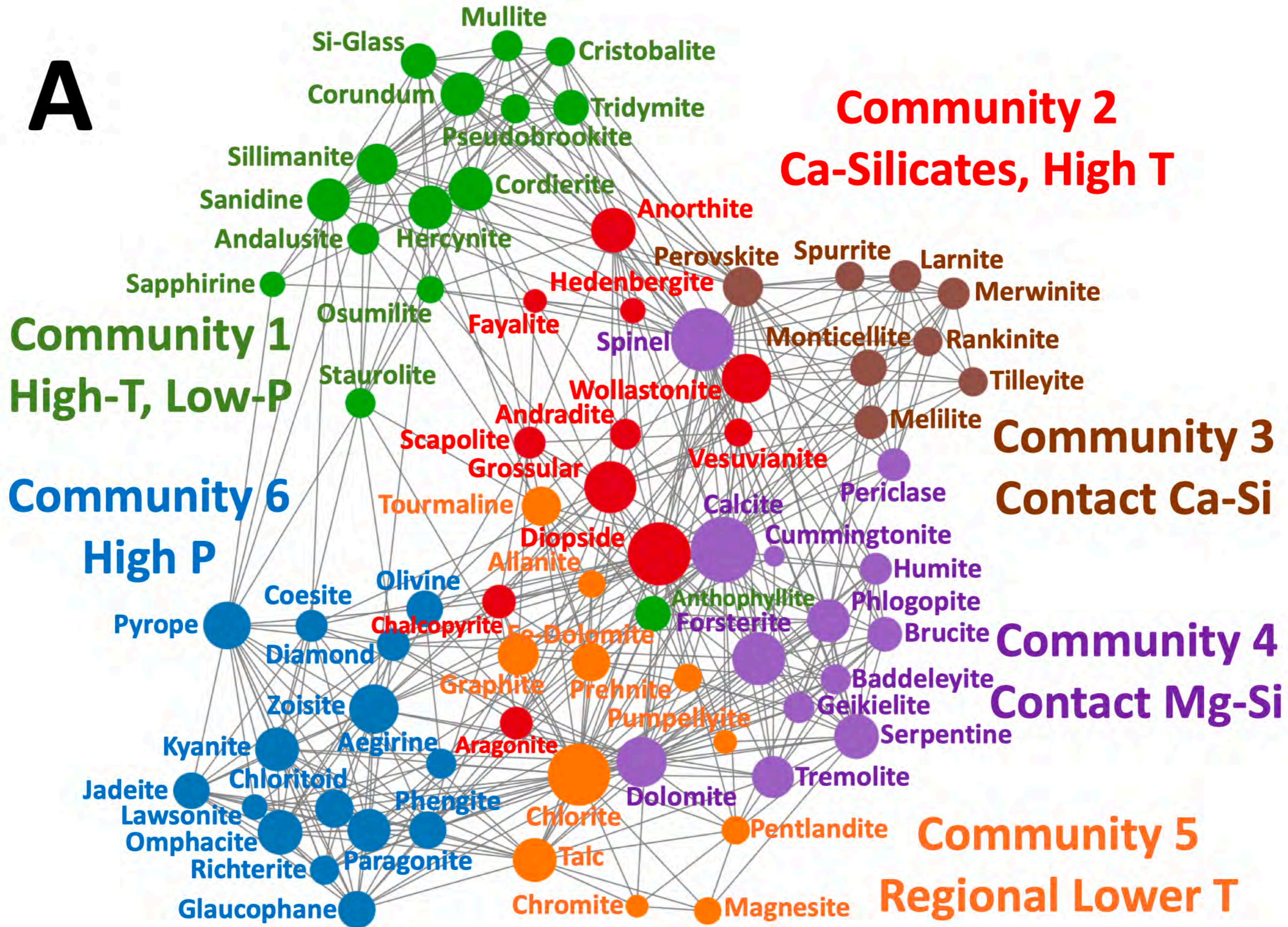
2515 To these framework silicates, we add *silicate glass* [(Si,Al,Ca,Mg,Fe)O; SiO₂ > 70 wt %; with
2516 68 occurrences] as an important yet often poorly characterized metamorphic phase in thermal
2517 metamorphic environments, particularly of arkosic sandstones and pelites (Reverdatto and
2518 S6bolev 1973; Grapes 2006). Two varietal names of metamorphic glass are “buchite,” which
2519 forms when a silica-rich pelitic rock is altered by igneous contact, and “porcellanite,” a glass
2520 derived from pyrometamorphosed clay, marl, shale, or bauxite (Grapes 2006). Melting and
2521 glass formation may occur as low as ~650 °C at 0.5 GPa in a granite protolith, or > 1000 °C at
2522 low pressure and dry conditions. Grapes (2006) details how “Si-rich glass” in many
2523 pyrometamorphic zones typically contains significant Al₂O₃ and alkalis, a consequence of
2524 quartz-feldspar melting. Note that pure SiO₂ melts at 1700 °C—a temperature only attainable
2525 by lightning strikes or bolide impacts.

2526

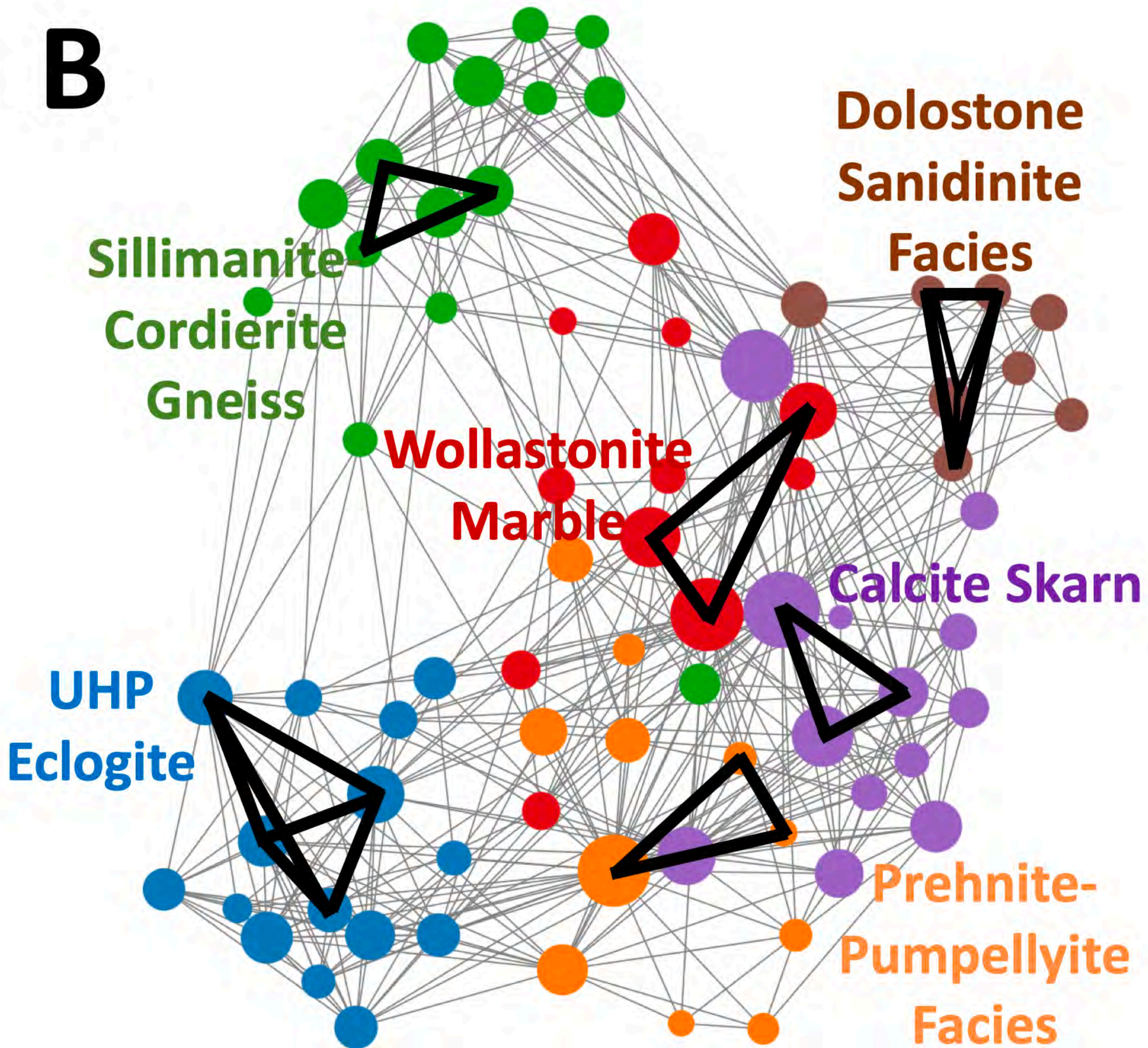
2527 *Rarer Metamorphic Minerals:* In addition to the 94 mineral kinds outlined above, 661 other
2528 mineral kinds occur rarely as trace phases in metamorphic rocks, as documented by reports in
2529 numerous primary sources and compilations, notably Anthony et al. (1990-2003) and
2530 references cited in <https://mindat.org> and <https://ruff.info/ima> (both accessed 20 January
2531 2023). Most of these scarce minerals, which are listed in Supplementary Table 1, were not
2532 recorded from any of the 2785 metamorphic rock modes in Supplementary Table 3.

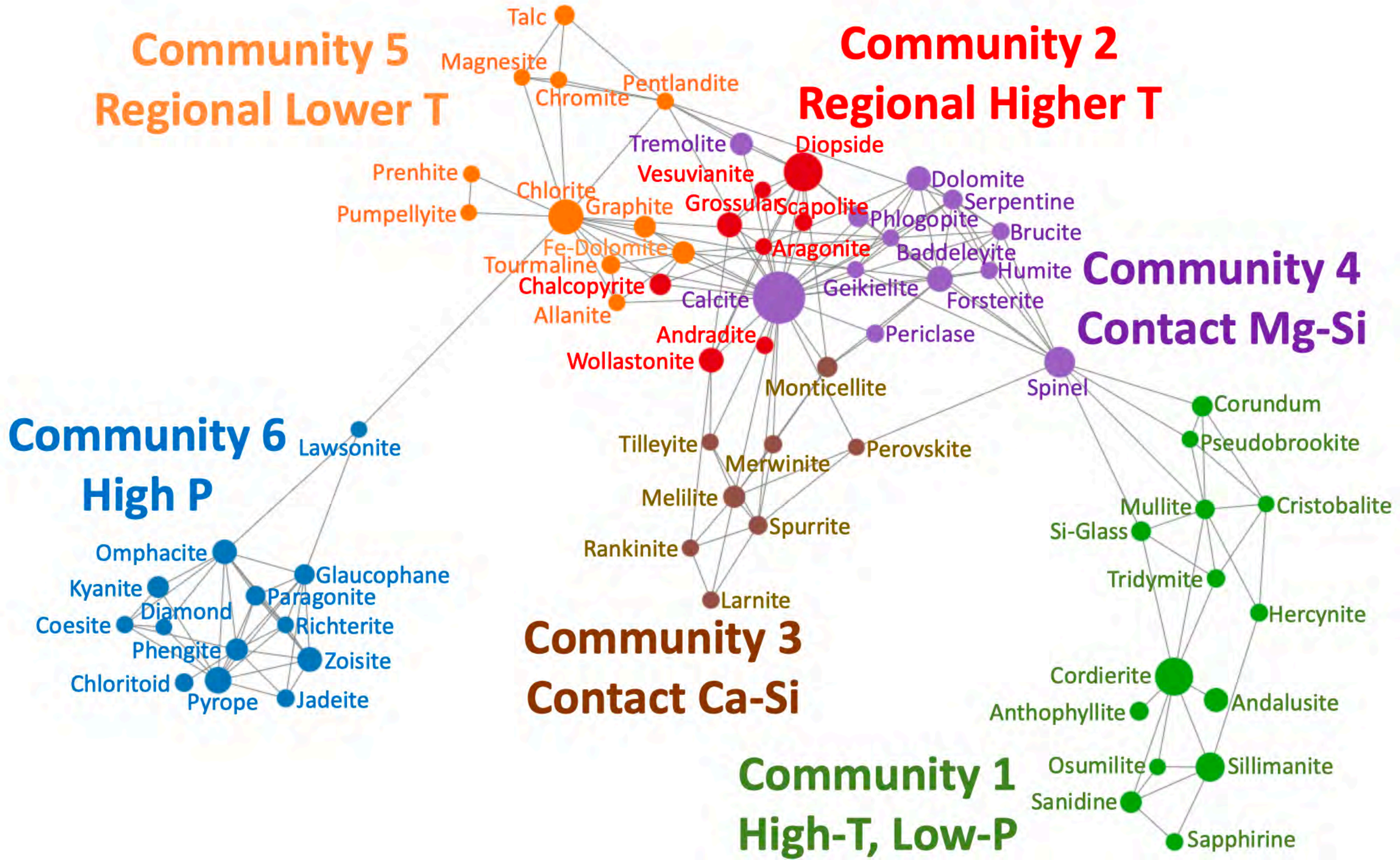
2533 However, a few of the less common minerals in Supplementary Table 1, were also noted in
2534 one or more metamorphic rock modes. Among these minor minerals, listed alphabetically, are
2535 *alleganyite* (1 occurrence), *analcime* (2), *anhydrite* (2), *ankerite* (6), *ardennite* (1), *arsenopyrite*
2536 (1), *axinite* (4), *bornite* (1), *braunite* (7), *bredigite* (6), *brownmillerite* (5), *bustamite* (4), *calzirtite*
2537 (3), *celestine* (1), *chondrodite* (4), *cuspidine* (2), *deerite* (2), *diaspore* (1), *fluorite* (1),
2538 *fluormayenite* (5), *friedelite* (1), *galaxite* (1), *giuseppeite* (1), *grunerite* (8), *hausmannite* (1),
2539 *hillbrandite* (1), *högbomite* (2), *ilvaite* (2), *jacobsite* (1), *kalsilite* (5), *kornerupine* (1), *kutnohorite*
2540 (1), *laumontite* (1), *leucite* (2), *margarite* (1), *monazite* (3), *nepheline* (4), *norbergite* (1),
2541 *piemontite* (7), *pigeonite* (2), *pyrophanite* (1), *pyroxmangite* (2), *qandilite* (3), *rhodocrosite* (2),
2542 *rhodonite* (8), *riebeckite* (4), *scawtite* (1), *siderite* (9), *sonolite* (1), *sphalerite* (9), *spessartine* (9),
2543 *stilpnomelane* (3), *suenoite* (5), *tephroite* (1), *thompsonite* (3), *uvarovite* (2), *wairakite* (2), and
2544 “zeolite” (6).

A



B





Community 5
Regional Lower T

Community 2
Regional Higher T

Community 4
Contact Mg-Si

Community 6
High P

Community 3
Contact Ca-Si

Community 1
High-T, Low-P

